Wildfires and aliens: differenced Normalized Burn Ratios (dNBR) indicate that woody invasive plants increase fire intensities in montane forest-grassland mosaics of the Western Ghats, India

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Abstract

Fire is a common disturbance in tropical and temperate savanna and grassland ecosystems. The impact and intensity of fire are strongly influenced by available fuel loads, local plant community composition and structure. Invasion by exotic species in grasslands can alter fuel availability and contiguity and, consequently, influence several aspects of the fire regime such as intensity, frequency and spread. Woody invaders in grasslands, in particular, have the potential to alter fire regimes significantly as they have starkly different structural and physiological characteristics from the native grasses. In this study, we assessed how three woody invaders - *Acacia mearnsii* (black wattle, or wattle), *Cytisus scoparius* (scotch broom) and *Ulex europaeus* (common gorse, or gorse) impacted fire intensities in the montane grasslands of the Nilgiri Biosphere Reserve, in the southern Western Ghats, India. We used the differenced Normalized Burn Ratio (dNBR) as an index of fire intensity. Our results indicate that invaded areas burned at higher intensities than native grasslands. Fire intensities were highest in areas invaded by gorse, followed by black wattle and scotch broom. Fire relationships with long term landscape changes like invasion are currently understudied, and such studies highlight the cascading impacts for ecosystem dynamics like fire with such changes. We also find that such increases in fire intensities as a result of woody plant invasion can potentially have long term consequences for community and ecosystem processes in this landscape.

1 Introduction

Fire is an important feature of several tropical savanna and grassland ecosystems (Keeley, 2006; Bowman et al., 2009). Fires open up vegetation and initiate secondary succession pathways (D'Antonio & Vitousek, 1992; Blair, 1997; Brooks, D'Antonio, et al., 2004; Sankaran, et al., 2005; Mandle et al., 2011; Hiremath & Sundaram, 2013) and can thus alter plant community composition and structure. Conversely, plant community composition and structure also determine fuel availability, flammability and contiguity, and can thus strongly influence fire patterns and characteristics (Burton et al., 2019; Ferreira et al., 2020).

Invasions of grasslands by woody exotics, both trees and shrubs, is a widespread phenomenon and a serious threat to grassland ecosystems worldwide (Keeley, 2001; Driscoll et al., 2010; Sundaram & Hiremath, 2012; Srinivasan et al., 2012a; Boudiaf et al., 2013). Such invasions can alter fire dynamics by influencing both species composition and vegetation structure, and in turn fuel characteristics (Bond & Parr, 2010). Because woody invaders in grasslands have different physiological characteristics from the native grasses (e.g C3 woody plant invasion vs C4 grasses), they can have particularly drastic effects on fire regimes (D'Antonio, et al., 2004; Bond & Parr, 2010; Mandle et al., 2011). Woody plant invasions in grasslands can alter fuel properties such as load, packing ratios, continuity, and spatial, vertical and horizontal structure. These alterations can strongly determine fire frequency, seasonality and intensity, depending on the physiology and ecology of the invasive species (D'Antonio, et al., 2004; Driscoll et al., 2010; Mandle et al., 2011; Estes, et al., 2017). Further, differences in vertical structuring of vegetation caused by woody invasives can, in some cases, change fire typology from surface fires to crown fires (Van Wilgen et al., 1998). At present, even though the effects of grass invaders on fire regimes have been extensively studied (D’Antonio & Vitousek, 1992; D’Antonio, et al., 2004; D'Antonio & Vitousek, 2016), the effects of woody plant invasion on grassland fire regimes are not fully understood.

In this study, we characterized the effects of invasion by three woody species on fire intensities in montane grasslands of the Nilgiri Biosphere Reserve (NBR), in the Southern Western Ghats, India. The upper elevations of the NBR are characterized by a unique forest-grassland mosaic, with stretches of tropical montane grasslands interspersed with pockets of stunted tropical evergreen forests, called ‘sholas’, in the valleys. Of the many exotics introduced in these grasslands over the years, three woody species have become particularly invasive, namely *Acacia mearnsii* (Black wattle, or wattle), *Cytisus scoparius* (Scotch broom) and *Ulex europaeus* (common gorse, or gorse; Joshi et al. 2018). Specifically, we used the differenced Normalized Burn Ratio (dNBR), which quantifies fire intensity based on the analysis of satellite images taken before and after a fire (Key & Benson 2006), to characterize fire intensities in uninvaded grassland and patches invaded by the three woody species following a wildfire that occurred in the last week of February, 2017. The dNBR is based on Near Infrared (NIR) and the Short-Wave Infrared (SWIR) bands which have high sensitivity to changes in vegetation caused by fires. NIR is absorbed the most following fires, while SWIR is reflected the most. The dNBR can discern minor changes in vegetation characteristics after a fire, such as in the amount of green cover and charring; by measuring changes in biomass loss, carbon release and smoke production (Key & Benson, 2006; Miller & Thode, 2007; Richardson et al., 2016).

Specifically, we asked: 1) How does invasion by woody species affect fire intensities relative to uninvaded grasslands, and does the effect differ between the three woody invasive species? Because topographical parameters like slope and aspect can also affect fire intensity both directly and indirectly by influencing the rate of fire spread and relative availability of moisture in the fuel (Emery & Gross, 2005; Hamman et al., 2011), we additionally asked: 2) How does topography influence the relationship between woody plant invasion and fire intensity?

2 Methods

2.1 Study site

The study was conducted in the Avalanche and Korakundah ranges of the Nilgiris Forest Division which is part of the Nilgiri Biosphere Reserve in the Southern Western Ghats (Fig. 1). The elevation of the site ranges between 1900m to 2400m. The Reserve receives an annual average rainfall of ~ 2000mm, the bulk of which is received between June and September during the Asian South-West Monsoon (Joshi, Ratnam & Sankaran, 2019). Average minimum and maximum temperatures vary from 0°C to 29° C. January is the coldest month of the year with a mean temperature of 5°C. The vegetation in the region consists of perennial C4 tussock grasses dominated grassland, with pockets of sholas which have stunted trees of several Western Ghats indigenous evergreen forest species (Caner, et al., 2000). Fires occur every few years in the post winter, pre-monsoon dry season (Arasumani et al., 2018).

2.2 Invasion history in the study site and wildfire event

Many exotic species were introduced into the Nilgiri grasslands during the British Colonial era (Joshi, Sankaran & Ratnam, 2018) of which, three became quickly established and rapidly started invading these grasslands. Wattle was introduced for fuel wood and for the commercial extraction of tannins, while scotch broom and gorse were ornamental. Until about a century and a half ago, these grasslands were periodically burned by the native pastoralist Toda community to release fresh flushes of grass for their cattle (Srinivasan, Bhatia, & Shenoy, 2015; personal communication with Toda elders). This region was declared 'protected' in 1972 and since then the management regime has actively suppressed fires (Hiremath & Sundaram, 2013; Das, et al., 2015), yet small fires are often reported during the dry season of December to March.

Black wattle, scotch broom and gorse are perennial leguminous plants of the Fabaceae family (Brown & Ko, 1997, Di'Tomasso, 2005; Leary, Hue, Singleton, & Borthakur, 2006, Muir & Vamosi, 2015). While black wattle is a tree and grows, on average up to 10m in height, both scotch broom and gorse are shrubs that grow between 1 and 3m in height (MacCarter & Gaynor, 1980; Brown & Ko, 1997; Rees & Payntert, 2009). These three species are also reported as invasives in Canada, South America, South Africa, New Zealand, Hawaii and North America (MacCarter & Gaynor, 1980; Bossard & Rejmanek, 1994; Pieterse & Boucher, 1997; Davies, 2006; Leary, et al., 2006; Anderson & Anderson, 2010; Paynter et al., 2010; Burrows, Cieraad, & Head, 2014). All three grow and expand as patches, forming distinct edges with the surrounding grassland, and significantly altering fuel availability and packing ratios (Brown & Ko, 1997; Watt et al., 2003; Brooks, Antonio, et al., 2004; Mandle et al., 2011; Srinivasan et al., 2012b). As a result, the invaded landscape is a mosaic of patches of the three invasives interspersed with native grasslands and shola forests (Srinivasan et al., 2012b and Fig. 2).

2.3 Map of invasion within the fire boundary

We evaluated the effects of woody plant invasion on fire intensities following a fire that occurred in February, 2017 that burnt an area of 6.3km^2. The entire boundary of the fire was mapped in November 2017, seven months after the fire. Tracks were recorded and waypoints were collected every 50 m on a handheld Garmin etrex 30 GPS receiver (Garmin international Inc., 2011). These were transferred to QGIS (**QGIS** Development Team) and used to digitize the fire boundary by overlaying them on very high-resolution satellite imagery (Google Earth (Version 5.1.3533.1731)).

In order to obtain an accurate spatial map of the initial, pre-fire land cover of the burnt area, every invaded patch was physically surveyed and mapped during February and March, 2018. A GPS Waypoint was marked at the center of each invasive patch, and the approximate dimensions of the patch, presence and the relative area covered by individual stems or trunks of these invasives and other species within the same patch was noted. High resolution imagery from Google Earth was then used as the base layer to digitize every single invasive patch in the study area. Water bodies, patches of shola forests and rocky outcrops were also digitized.

Cloud free LANDSAT 8 images (Landsat-8 image courtesy of the U.S. Geological Survey) from 3rd February, 2017 (just before the fire) and 8th April, 2017 (just after the fire) were obtained from the U.S

Geological Survey Earth Explorer portal for the estimation for fire intensities. Following image pre-processing, which included cloud cover masking and conversion from Top of Atmosphere (TOA) reflectance to Surface Reflectance, normalized burn ratios (NBR) values for both the pre- and post-fire periods were estimated as (NIR – SWIR)/(NIR + SWIR). The dNBR value of each 30x30m pixel was then calculated as the difference between pre- and post-fire NBR values. Topographic slope values were obtained from ASTER DEM imagery (ASTER DEM image courtesy of the U.S. Geological Survey).

2.4 Statistical methods

We used linear regression models to estimate the relationship between dNBR values as the response variables, with slope, invasives' presence and abundance as predictors. All statistical analyses were carried out using R and R studio (version 3.5.0 (2018-04-23) – "Joy in Playing") (R core team, 2018).

3 Results

Relationship between invasion and fire intensity

Fire intensities, as indexed by dNBR, were quite variable across the burnt landscape (Fig. 4). The lowest fire intensities were recorded in native grasslands and in patches invaded by scotch broom which had similar fire intensities as native grasslands (p value = 0.644; Fig. 5). Invasion by wattle and gorse significantly increased fire intensities as compared to uninvaded grassland ($p < 0.0.5$ in both cases; Fig. 5). Fire intensities were highest in patches invaded by gorse followed by wattle (Fig. 5). While the lower limits of intensities recorded were similar across the landcover types, higher intensity fires were recorded more often in invaded patches (Fig. 5). However, contrary to our expectation, slope had no effect on fire intensity, in both invaded and uninvaded areas.

In general, fire intensities increased as the proportion of area covered by invasive species within a grid cell increased (Fig. 6), particularly in the case of gorse (slope = 0.81, p value < 0.01, $R^2 = 0.31$). However, the relationship between fire intensity and proportion of the grid area invaded was weak for grids invaded by scotch broom (slope = 0.16, p value = 0.01, $R^2 = 0.05$) and wattle (slope = 0.19, p value < 0.01, $R^2 = 0.06$). The highest fire intensities (dNBR ~ 1.3) were recorded in grids fully invaded by black wattle and gorse.

4 Discussion

The results of this study indicate that invasion of grasslands by exotic woody plants in this montane forest-grassland mosaic alters fire intensities, with areas invaded by gorse and wattle typically burning more intensely than uninvaded grasslands or grasslands invaded by scotch broom. Further, the extent to which fire intensities increased was contingent on the magnitude of invasion; pixels with a greater cover of woody invasive plants typically burnt more intensely than those with a lower cover of woody invasives.

The observed difference in burn intensities of patches invaded by the different species is potentially a consequence of differences in fuel loads, fuel architecture and moisture retention capacities of the three species. Gorse has been reported to be very highly flammable, with relatively low moisture retention and burns well due to its high fuel packing ratio (McCarter & Gaynor, 1980; Grace et al., 2002; Marino, et al., 2011). Flammability of black wattle patches on the other hand can vary depending on the girth and maturity levels of the individual plants. Younger patches with smaller individuals tend to have low flammability while older patches with larger individuals have high flammability (Brown & Ko, 1997; Pieterse & Boucher, 1997; Anderson & Anderson, 2010). The high variability in the burn intensity observed in wattle invaded patches in our study is possibly a consequence of the spatial variation in age and sizes of individuals across wattle patches in the study site. Fire intensities in patches invaded by scotch broom, on the other hand, did not differ significantly from uninvaded grasslands in our study. Although scotch broom is flammable in the dry season, it has been reported to retain higher levels of moisture when compared to the other species during wetter seasons (Rice 2005). The lack of a significant effect of scotch broom invasion on fire intensities in our study could potentially be a consequence of the fire occurring early in the dry season when scotch broom plants still retained fair amounts of moisture. It is possible that fire intensities in patches invaded by scotch broom would be significantly greater than uninvaded grasslands for late-season fires, but this remains to be tested.

Although fire intensities were highest in gorse-invaded patches, a previous study in the same area reported that gorse also regenerated the fastest amongst the three invasive species (Sriramamurthy, Bhalla & Sankaran, 2020). Mortality of gorse following fires was quite low, with most gorse individuals re-sprouting (coppicing) following burning. On the other hand, fires resulted in the mortality of most established wattle and scotch-broom individuals (Sriramamurthy, Bhalla & Sankaran, 2020), with most of the post-fire recruitment of these two invasive species occurring through the seed bank. The ability of gorse to encourage more intense fires, while also being able to recover rapidly following fires, can potentially give this species an advantage under frequent fires, but further studies are required to substantiate this claim. Such species-specific differences in fire intensities can also have potential consequences not just for post-fire regeneration of the three invasive species, but also for native plant communities in the study area. Although one previous study has characterized post-fire regeneration of native species in patches invaded by scotch broom, we are unaware of any studies that have done this for patches invaded by the other two species, precluding any comparison at the present time.

5 Conclusion

Openly accessible satellite imagery and derived indices such as dNBR are useful tools for low cost, remote and effective monitoring of spatially diverse landscapes such as our study area where fire is an important feature. Our results indicate that woody plant invasion in these grasslands is fundamentally changing fire regimes in this system, with potential longer-term consequences for native plant communities in the area. Future ground-based studies that quantify fire intensities in patches invaded by the three species and monitor changes in post-fire vegetation communities can help better calibrate such remotely sensed indices and provide us with a more nuanced understanding of invasive species effects in this system.

6 End Materials And Declarations

6.1 Originality of work and declarations

The authors declare that they report original research in this manuscript and any references to existing content have been cited and quoted as applicable and due permissions have been obtained. This manuscript has not been submitted elsewhere. This manuscript describes a new result of an existing investigation, and the background data is similar to another publication by the same investigators, added in the references section (Sriramamurthy et al., 2020). The background data is subject to be similar to the background data and information of the previous publication. No human subjects were involved in the study.

6.2 Data sourcing statement

Landsat data are freely available on the USGS website. The images used here were downloaded from the USGS website. The images that this manuscript has used have not been enhanced or obscured to falsely introduce any feature.

6.3 Author contributions

All authors have contributed to the ideation, study design, data collection, analysis and reporting of this study. Following the CASRAI's CRediT (Contributor Roles Taxonomy) schema, here is the contribution of each of the authors: Sriramamurthy, R. T. has contributed to the conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft and writing – review & editing parts of the work, while Sankaran, M. and Bhalla, R. S. have both contributed to the conceptualization, formal analysis, funding acquisition, methodology, resources, supervision, validation, writing – review & editing parts of the work.

If, in the future, we discover any error in our published work, we take the responsibility of notifying the journal and take situation-appropriate action.

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Figures

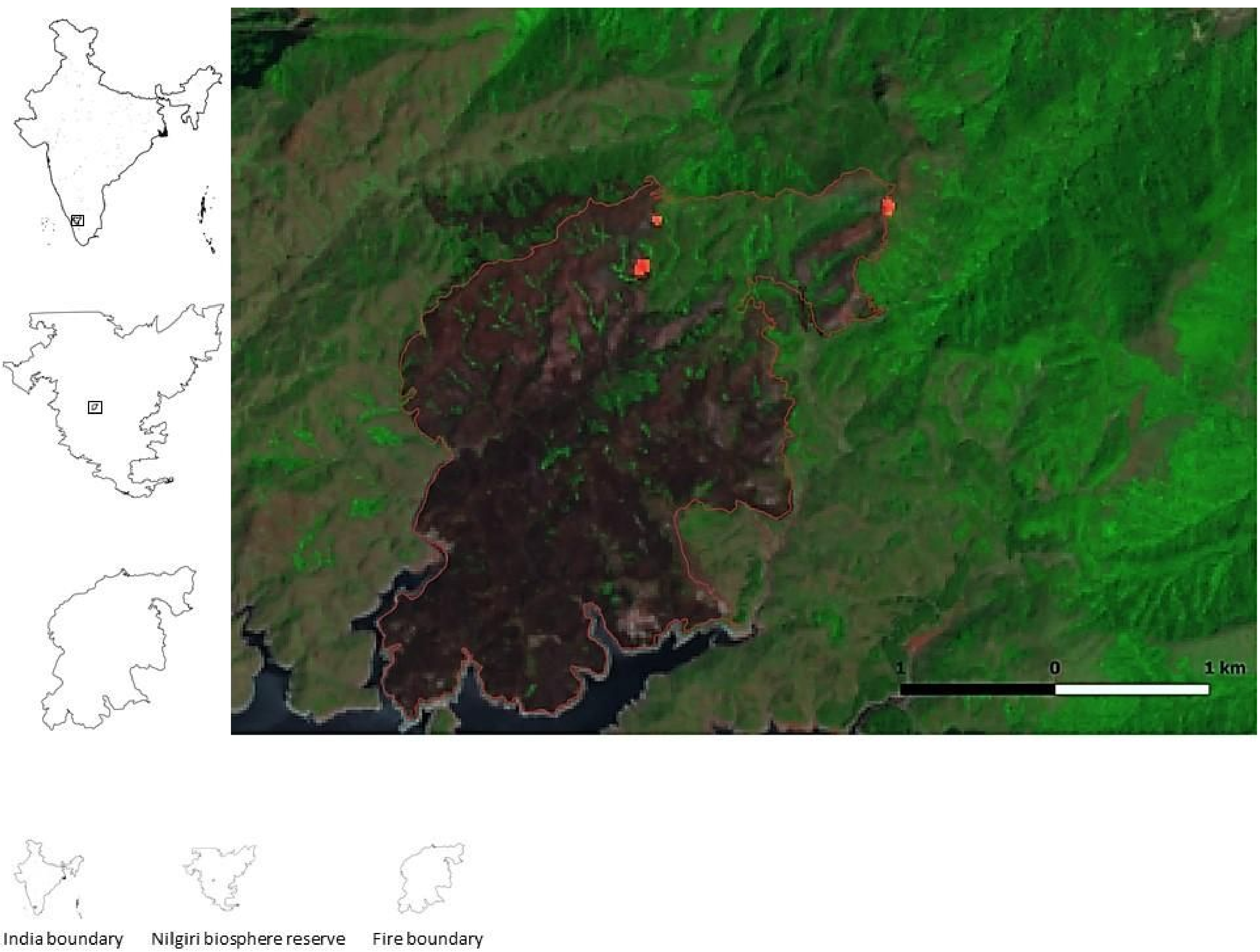

Figure 1

A map of the study area within the Nilgiri Biosphere Reserve in the Southern part of the Western Ghats in Peninsular India (top inset). Active fires are visible on the North East of the fire boundary which is shown in red. The blackish brown patch is the burnt area of a fire that occurred in the Avalanche Reserve Forest in the last week of February, 2017. The satellite image of the fire has been reproduced from Sriramamurthy et al., 2020.

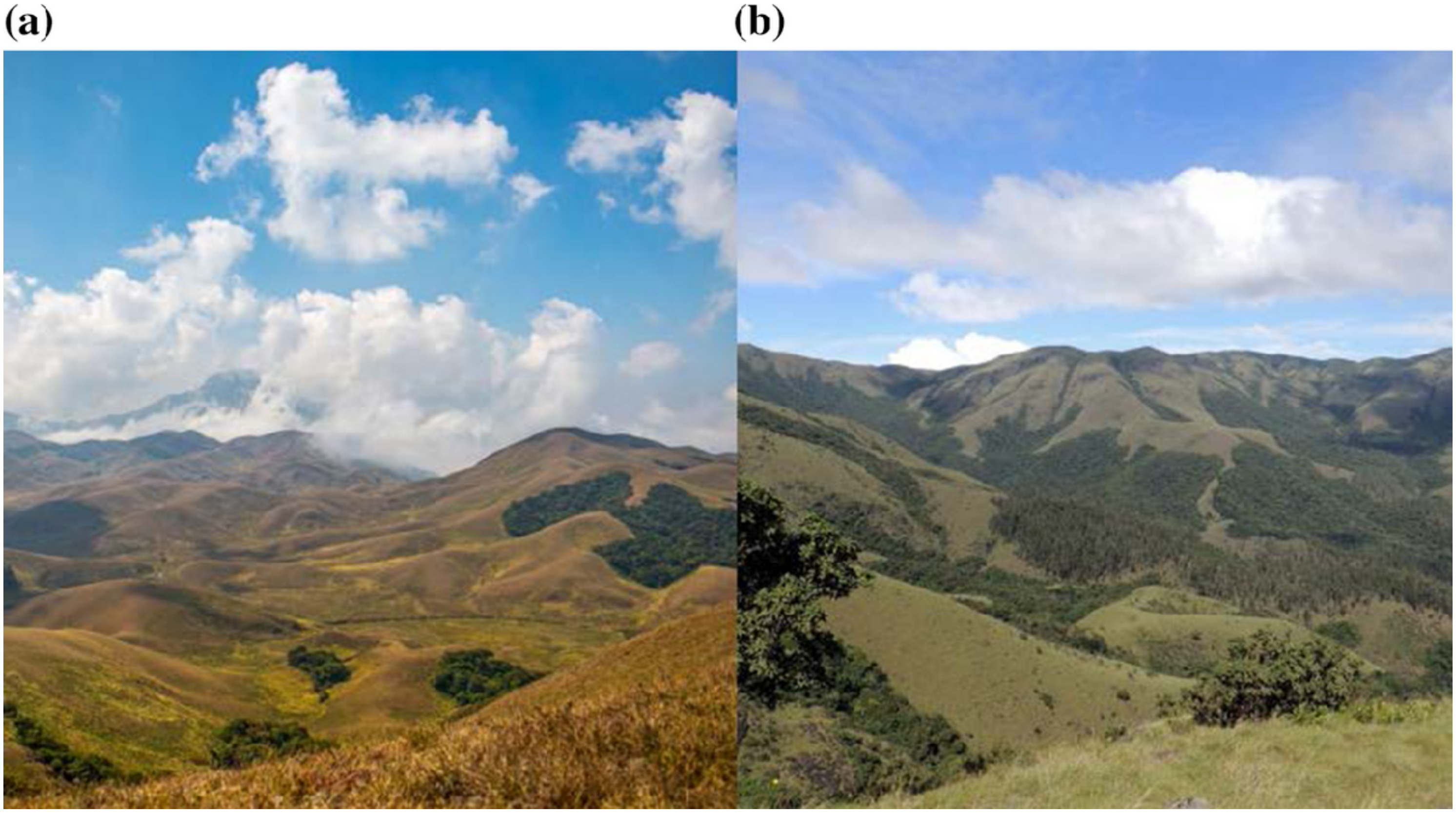

Figure 2

Left panel – pristine shola grasslands with forests in the valleys (image from Prasenjeet Yadav). Right panel - invaded shola grasslands with large tracts of grasslands on the slopes covered by introduced exotics. The brownish green patches of vegetation in the middle of the photo are invaded areas.

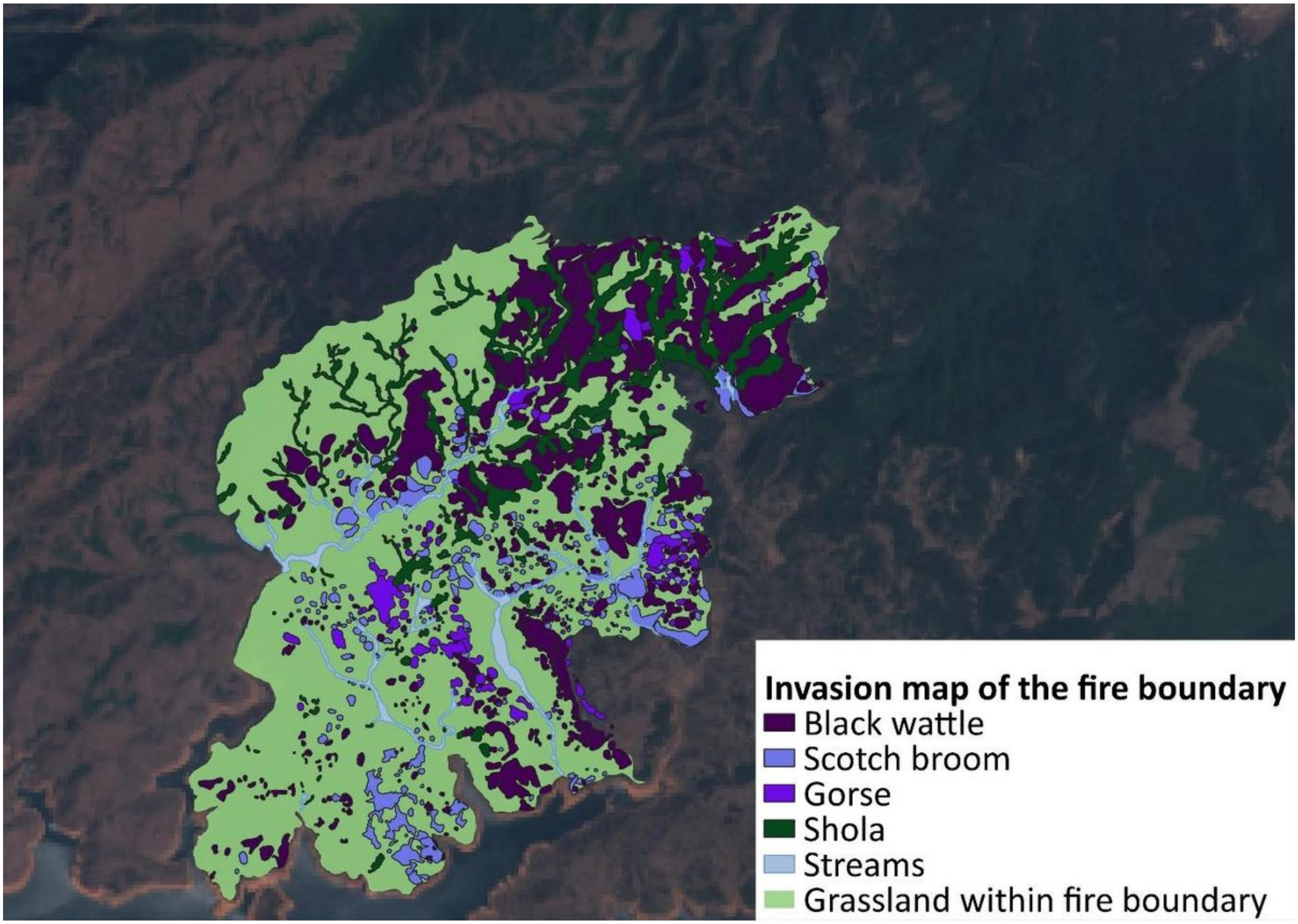

Figure 3

Digitized ground cover invasion map of the burnt area.

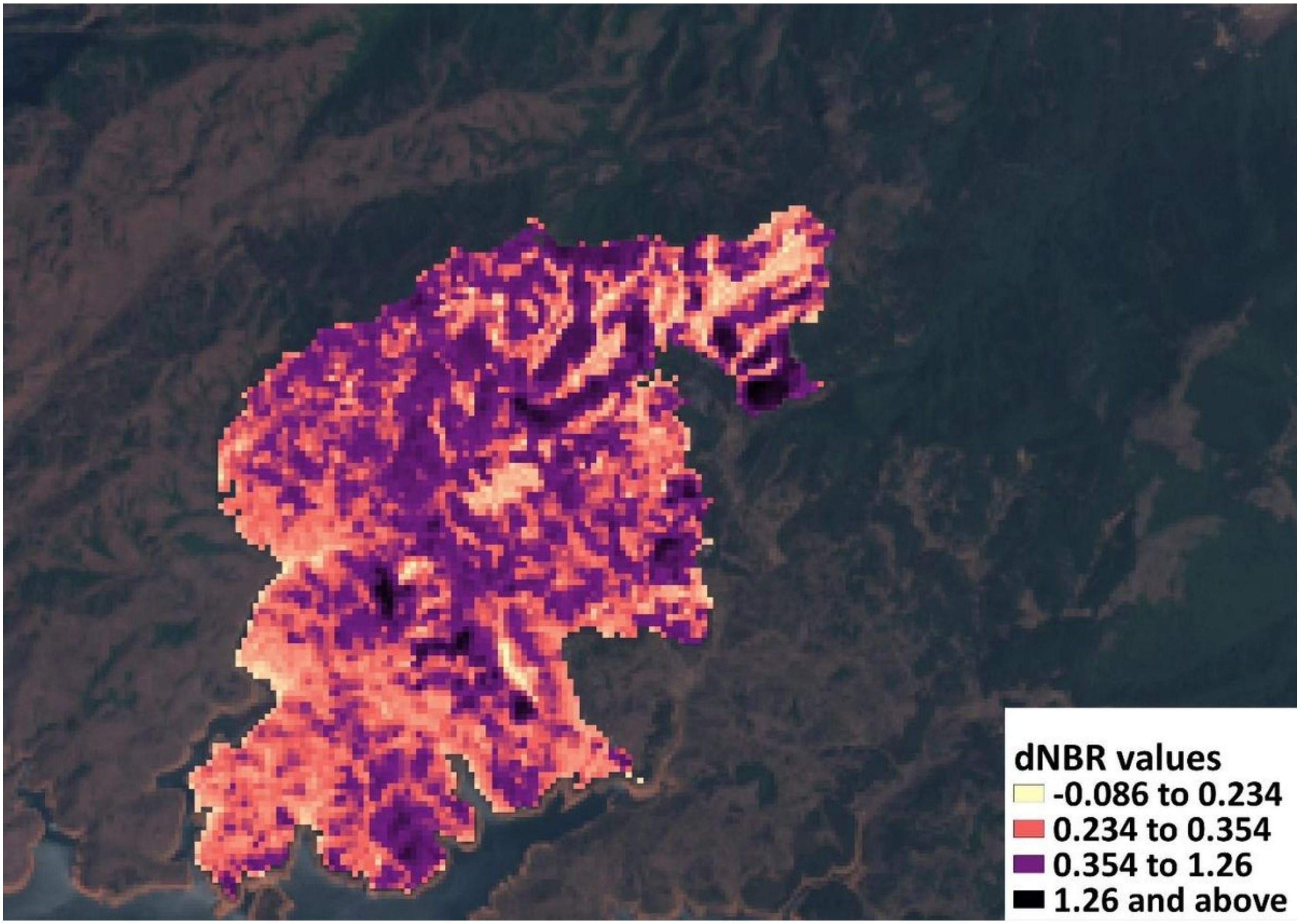

Figure 4

dNBR image of the burnt patch from immediately following the fire. The darker colours indicate areas that had burned more intensely.

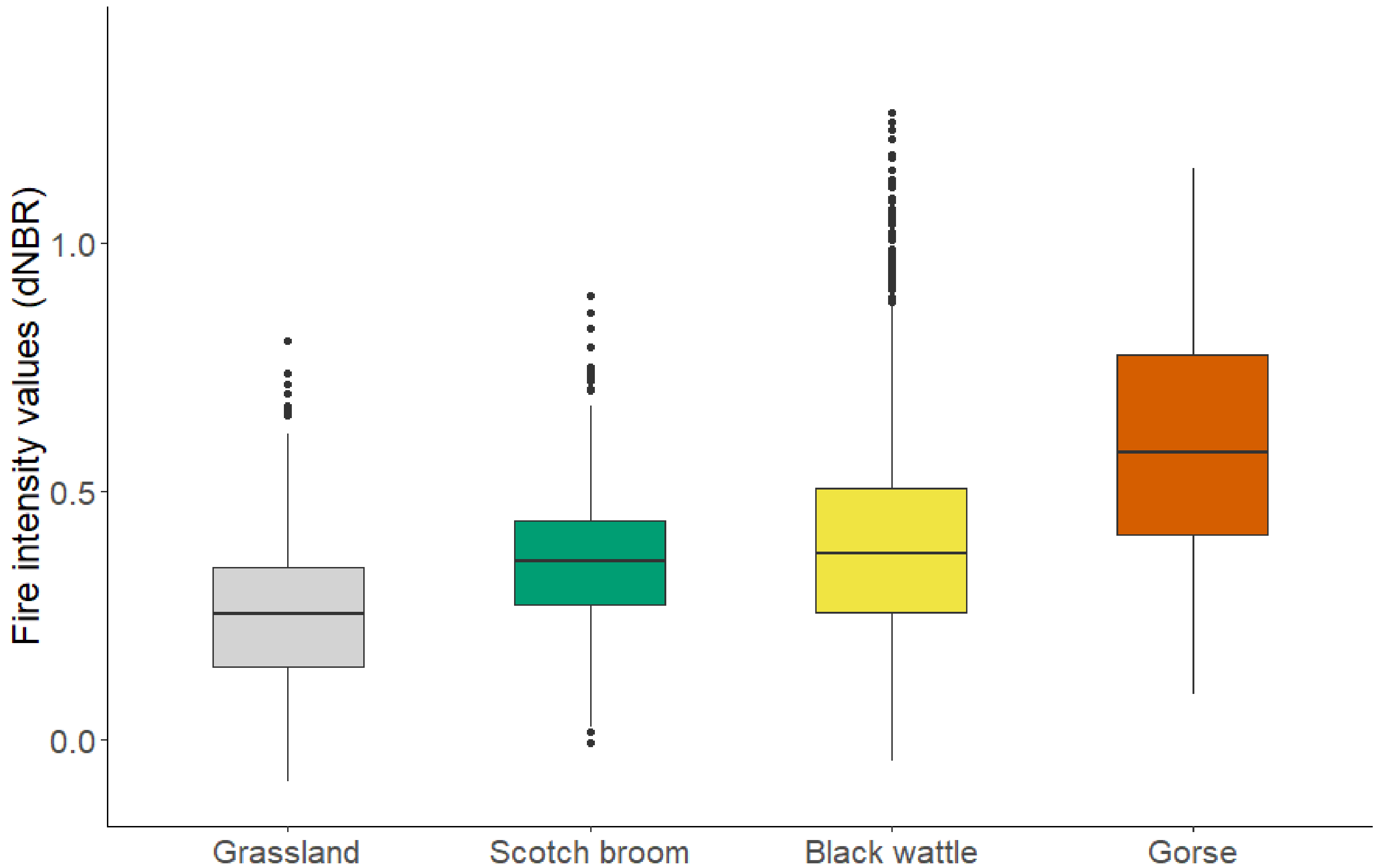

Figure 5

Boxplots of variation and range of fire intensity values in different land covers - native grassland and grassland invaded by scotch broom, wattle or gorse. The native, uninvaded grassland has the lowest median fire intensity value.

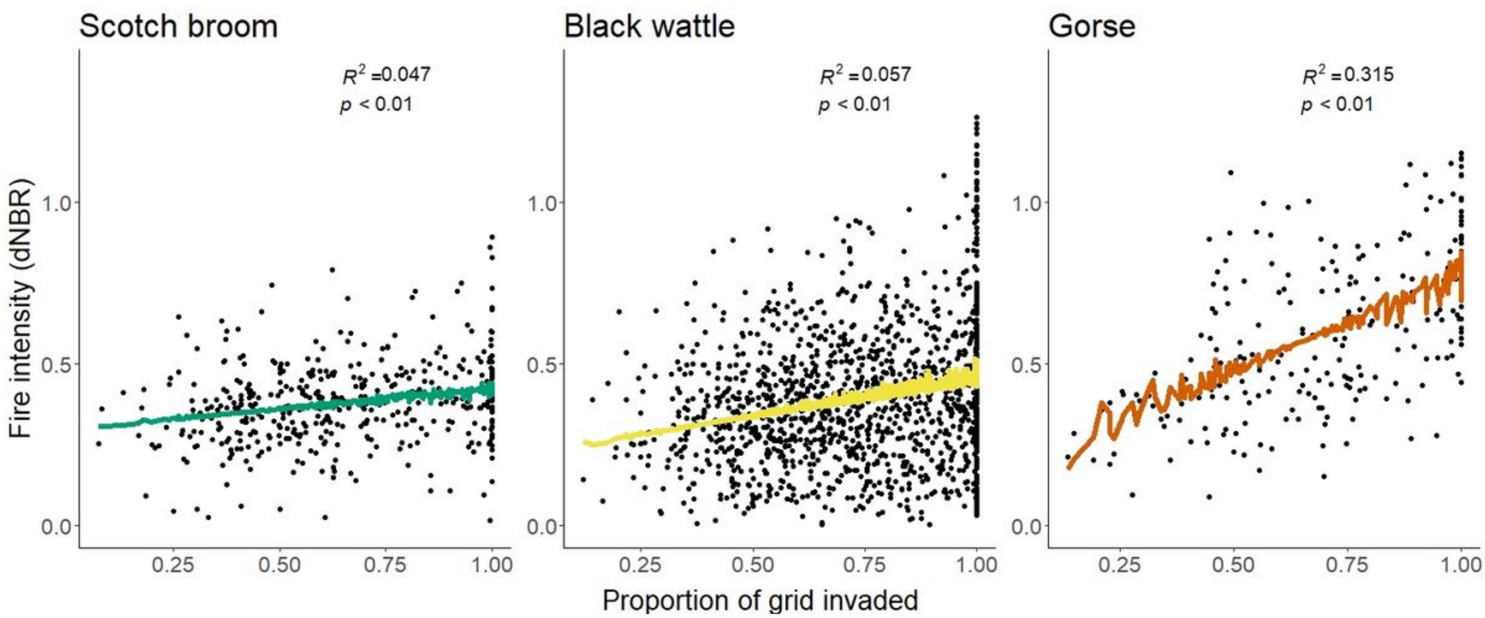

Figure 6

Regression between invasive abundance and fire intensity values in a grid. Fire intensity increases with extent of invasion and does so most steeply for gorse, and least for scotch broom.