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Demographic processes and fire regimes interact to influence plant population trajectories under changing climates

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Abstract

Fire regimes are changing around the world raising important questions about the risks to biodiversity. Fire seasons are lengthening, high-severity fires are occurring more often and in unexpected places. Extensive research examines some of the fire related risks to life and property. However, in the fire risk research space there is often limited or simplified inclusion of ecological values. Future fire regimes, alongside climatic change, could have profound impacts on biodiversity conservation and ecosystem function. For example, plant population trajectories can be influenced by demographic traits, disturbance regimes and environmental variables such as climate. Climate change can affect all three and is likely to impact on plant populations through altering natural fire regimes as well as influencing species demographic traits. These changes are unlikely to be unidirectional with some plant types benefiting and others being disadvantaged. Here, we examine the impacts of climate change both on the shifts in fire regimes alone and combined with predicted climate-induced demographic shifts. We use two functional plant types (obligate seeder, facultative resprouter) in a number of case-study areas representing woodland-dominated landscapes of south-eastern Australia. We link a fire regime simulation tool with a spatially explicit population viability analysis model. We simulate fire regimes under six different future climates representing different temperature and precipitation shifts, and 16 demographic change scenarios, characterised by changes to individual or multiple plant demographic processes. Obligate seeder species were predicted to be less resilient to changes in demographic parameters. However, both resprouter and seeder species were found to be negatively affected by the combined impacts of changes to multiple demographic parameters or to a combination of a shifting fire regime and changes to demographic traits, particularly through simulated reductions in adult survival. To our knowledge this is the first study to integrate fire regime simulations with spatially explicit population viability analyses. Such an approach significantly increases our ability to identify which functional types are most at risk of population extinction under predicted fire regime and demographic changes. This flexible framework is an important first step in exploring the complex interactions that determine plant viability under a changing climate and will increase our ability to prioritise research and fire management for biodiversity into the future.

1. Introduction

Fire is instrumental in shaping plant community composition (Pausas & Ribeiro, 2017). Many plants are adapted to components of the fire regime (e.g., fire severity, inter-fire interval), through fire-adapted traits, which typically offer two main strategies in the face of fire, survive fire or regenerate following fire (Enright & Goldblum, 1999). Species that rely on one strategy are termed obligate (e.g., an obligate seeder can only regenerate through seeds), and those that are more flexible in their regeneration strategy are termed facultative (e.g., a facultative resprouter can both resprout and produce seeds, Clarke et al., 2015). Resprouting species can survive fire by producing new shoots from meristematic tissues, either above ground from buds on the trunk and branches (epicormic resprouter) or from basal tissues when above-ground tissues are killed or damaged (basal resprouter, Pausas & Keeley, 2014). Groups of species that share fire-adapted traits are often grouped into functional types, which typically describe key processes that contribute to species dynamics (Noble & Slatyer, 1980, Pausas, 1999). Responses of plant populations to fire are thus often described in terms of functional types and associated traits, including whether seeds are stored in the canopy or soil, and whether seed germination is fire cued or can occur without fire (Noble & Slatyer, 1980, Pausas et al., 2004, Pausas & Keeley, 2014).

The interactive effects of a potentially warmer drier climate alongside changes to the fire regime have the potential to increase the extinction risk of plant species through demographic changes (Enright et al., 2015). Plant demographic rates can also vary across climate gradients, with vital rates generally decreasing under warmer conditions (Bowman et al., 2014), and therefore may change as the climate changes. Many demographic traits are directly related to a plant species' fire response. For example, fire-responsive species could be at increased risk of localised extinction if future warmer drier climates decrease growth rates and associated time to maturity (Bowman et al., 2014, Enright et al., 2014, Jump et al., 2006) or decrease seed production and post-fire recruitment (Miller et al., 2019). If fire frequency were to increase alongside demographic changes, the window for population self-replacement may be reduced due to the interacting effects of climate and fire, a phenomenon termed "interval squeeze" (Enright et al., 2015). Improved understanding of the interactions among plant demographic traits, fire regimes, and climate is critical to identifying those species at most risk in fire-prone vegetation communities.

Effective conservation management of any system needs to be based on sound predictions of ecological futures. However, as we move towards the potential for new interactions without historical analogues, we cannot solely rely on past empirical data. As our climate changes and fire regimes change alongside, we need to be able to untangle how variation in plant traits influence the viability of populations. Simulation modelling provides the opportunity to expand the utility of existing empirical data to examine plant population viabilities under various combinations of traits, fires, and climates. In Australia, the empirical, demographic data around fire responsive plant species is substantive, albeit patchy. Initiatives such as Austraits, a database of plants traits from Australian flora (Falster et al., 2021) provide a means for the collation of these into the future. Previous research of fire responsive plant species in Australia has mostly focused on single species where the demographic data are often collected over many years (e.g. Auld, 1986, Ooi et al., 2004, Swab et al., 2012). These investigations are invaluable. However, detailed demographic data for many species of interest are lacking across environmental gradients. Collecting such data and attempting to measure and interpret the relationships among fire, climate, and plant populations would be infeasible for all at-risk vegetation communities.

In this study, we develop a framework for simulating ecological futures, combining a landscape fire regime model with plant demographic data in the form of a spatially explicit population viability analysis. We use this framework to examine how a changing climate might affect demographic processes and fire regimes to influence plant population trajectories.

2. Model framework

Our modelling framework involved six steps:

1. Select study area and species;
2. Create fire raster layers based on six representative climate models;
3. Construct population transition matrices for fire and non-fire years based on demographic change scenarios;
4. Create habitat suitability layers for each selected species;
5. Build population trajectory models for 100-year simulations for each combination of fire regime and demographic change scenario; and
6. Compare outputs across scenarios, functional types, and study areas (Figure 1).

The two simulation programs used in the framework are FROST (Penman et al., 2015) and STEPS (Visintin et al., 2020). FROST (Fire Regimes and Operations Simulation Tool) simulates fire regimes over decades to centuries using a combination of fire event simulation tools (PHOENIX RapidFire: Tolhurst et al., 2008) and Bayesian networks to represent uncertainty. FROST is spatially explicit and produces fire data (cells burnt, intensity, frequency) at a 180 m resolution for each year of a simulation. STEPS (Spatially and Temporally Explicit Population Simulations) is a spatially explicit population dynamics R package (Visintin et al., 2020). It models species populations as a function of species ecological and physiological requirements, and disturbance and landscape dynamics. Spatially explicit FROST outputs of fire occurrence and severity are fed into STEPS to, for example, trigger a germination or resprouting event for a plant species or to trigger mortality within the simulation cell.

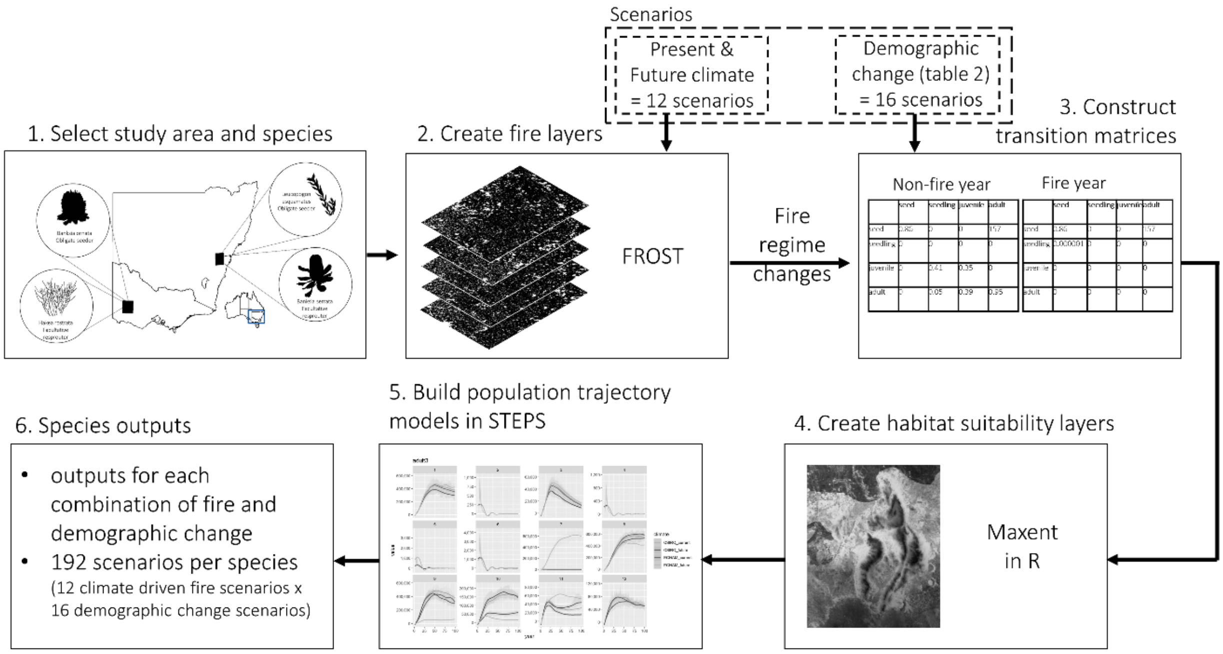

Figure 1 Modelling framework. Step 1: select the study area and species. Step 2: Create fire raster layers using FROST under six predictions of present climate and six predictions of future climate scenarios. Step 3: collate empirical data and expert advice to create population transition matrices for non-fire years and fire years for each species under 16 demographic change scenarios. The transition matrices are used to parametrise the population models with the PVAs. Step 4. Create habitat suitability layers using presence only data with the dismo package in R. Step 5: Build population trajectory models in the STEPS package in R for each combination of fire regime and demographic change scenario. Step 6. Examine species outputs under each combination of fire and demographic change scenario.

3. Implications

Demographic changes on plant population viability far outweighed impacts from a changing fire regime in our simulations. In general, obligate seeder species were predicted to be less resilient to changes in demographic parameters than facultative resprouter species. This introduces considerable challenges for management looking to improve ecological outcomes. The focus needs to shift towards management activities that relate directly to improving demographic outcomes such as protection of adult plants and ensuring adequate seed supply for active restoration. Due to the large number of interconnected mechanisms driving plant viability, there are still significant knowledge gaps that will require research to improve our understanding of how plant communities will respond to fire and demographic shifts.

4. Conclusion

The effects of future climate on biodiversity will be complex. Our study predicts changes in plant population trajectories due to climate effects on demography or climate effects on changing fire regimes and demography. The simulation results suggest we need to understand demography across climate gradients in order to prioritise species conservation. Therefore, field research that gathers demographic data is vital for protecting future ecosystems. Our PVA-fire regime simulation framework can address questions around management intervention through prescribed burning and fire suppression, and identify which demographic shifts an ecosystem may be most sensitive to. However, the importance of demographic shifts in our study emphasises the need for conservation managers to actively understand and appropriately manage at risk ecosystems to improve or promote resilience to future changes in climate.

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