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Interactions of biological and herbicidal management of *Melaleuca quinquenervia* with fire: Consequences for ecosystem services

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ABSTRACT

Exotic plant species invasion can alter ecosystem nutrient dynamics and natural disturbance patterns. The Australian tree *Melaleuca quinquenervia* has extensively invaded the Florida Everglades and is currently being suppressed using mechanical, herbicidal, and biological control management strategies. While these methods have been evaluated based on reductions in density and abundance of the target weed, other factors should be considered including consequences for ecosystem nutrient storages and interactions with natural disturbances such as fire. We hypothesized that the choice of management tactics, namely herbicidal or biological control, would differentially influence the quantity and availability of soil nutrients before and after a seasonal fire. The management of *M. quinquenervia* with a herbicide reduced the above- and belowground storage of nutrients both before and after a fire compared to a non-invaded area, while biological control increased storage. There were no differences in nitrogen availability between sites (non-invaded, herbicide, biological control) in the 0–5 cm or 5–15 cm soil depths before or after the fire. Pre-fire phosphorus availability was highest in the non-invaded site in the 0–5 cm soil depth and in the biological control site in the 5–15 cm soil depth. However, phosphorus availability was highest at both depths in the herbicide site post-fire. Biological control of *M. quinquenervia* using insect herbivores has proven to be effective at controlling plant growth and reproduction. The results of this study suggest that this method may have less of an impact on nutrient storage and cycling than herbicides.

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1. Introduction

Ecosystems invaded by exotic plants are often managed to maximize the delivery of services such as space for recreational activities, wildlife habitat, and maintenance of biological diversity. However, few evaluations have been done on the effects of management programs on less obvious, but no less important, ecosystem services such as nutrient storage and cycling. Tipping et al. (2008a) found that biological control of *Salvinia molesta* not only reduced the biomass and density of infestations in several Texas and Louisiana lakes, but also increased dissolved oxygen needed to support organic matter decomposition and aquatic life. Malcom et al. (2008) reported that lower, pre-invasion levels of soil nitrogen (N) were restored after the mechanical removal of the invasive tree *Robinia pseudoacaia* in a pine-oak system. This is biologically significant because plant induced increases in the level of available nutrients in the soil may promote fast-growing, invasive species (Huenneke et al., 1990; Davis et al., 2000; Ehrenfeld, 2003; Blumenthal, 2005).

Not all control programs are successful in restoring ecosystem services and any fundamental changes in the cycling and storage of nutrients may complicate the management of invasive plants. For example, despite the significant suppression of the invasive plant *Lupinus arboreus* by herbicides, soil available N was not restored to the lower pre-invasion levels in a California coastal dune (Pickart et al., 1998). Ogden and Rajmanek (2005) found that although the use of fire and herbicides did significantly decrease the cover of the invasive fennel *Foeniculum vulgare*, it was replaced by non-native Mediterranean annual grasses.

Longer-term management of invasive plants may have a cumulative effect on nutrient dynamics. This might include continuous and regular applications of herbicides to suppress aquatic vegetation in semi-tropical areas where plant growth occurs year round. For example, an average of 2461 ha of floating aquatic vegetation was treated each year with herbicides from 1975 to 1998 on Lake

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Okeechobee in central Florida (Grimshaw, 2002). These treatments were responsible for up to 17% and 49% of the external annual N and phosphorus (P) loads, respectively, for that lake which serves as a source of water for the Florida Everglades. Fundamental alterations in the timing and quantity of nutrient pulses may disrupt downstream native plant communities and allow invasive plants to maintain ecosystem dominance. In the northern Florida Everglades, a combination of disturbance and P loading has resulted in the large-scale replacement of the low-nutrient adapted species *Cladium jamaicense* with *Typha domingensis* (Newman et al., 1998).

Natural environmental perturbations can further complicate or exacerbate management efforts. Many natural areas depend on fire to maintain community structure and function by opening canopies, promoting seed release and germination, and providing temporary pulses of soluble nutrients (Wade et al., 1980; Neary et al., 1999). However, fire-adapted invasive species may benefit disproportionally from any increases in space and resource availability after fires (Hobbs and Huenneke, 1992; D'Antonio and Vitousek, 1992; Keeley, 2006). Once established, invasive species may also change the basic pattern and influence of fire in natural communities (Mack and D'Antonio, 1998; Brookes et al., 2004). For example, the invasive plant *Bromus tectorum* both increases the frequency of fires and permanently alters soil N dynamics thereby promoting its own persistence and dominance (Evans et al., 2001).

The Australian tree *Melaleuca quinquenervia* (Cav.) Blake, has successfully colonized and invaded natural areas within Florida including the fire-regulated *Pinus elliottii* Englem-*Taxodium distichum* (L.) L.C. Rich var. nutans (Ait.) Sweet eco-tone forest (Myers, 1984). High concentrations of essential oils found in *M. quinquenervia* have promoted destructive canopy fires which are more likely to kill native vegetation than the cooler ground fires that normally occur in the natural systems. These same fires trigger the release of massive amounts of *M. quinquenervia* seed which have resulted in the establishment of widespread monotypic stands of *M. quinquenervia* (Serbesoff-King, 2003). This sequence was repeated for decades allowing *M. quinquenervia* to colonize most freshwater ecosystems in South Florida until an integrated, interagency control program was created to suppress the weed in the 1980s (Van Driesche et al., 2010). Although these programs have been evaluated based on the quantity of plant biomass removed, changes in density, or reduction in rates of population spread, other evaluation factors need to be considered including their impact on non-target vegetation, alteration of nutrient cycles, and interactions with natural disturbances such as fire (D'Antonio and Meyerson, 2002; Denslow and D'Antonio, 2005).

The objective of this research was to elucidate the above- and belowground changes to a *P. elliottii*-*T. distichum* eco-tone forest after the invasion by and subsequent management of *M. quinquenervia*. In particular, emphasis was given to the management consequences for nutrient storage and availability before and after a fire. We hypothesized that the choice of management tactics, namely herbicidal or biological control, will differentially influence the quantity and availability of nutrients both before and after a fire.

2. Methods

2.1. The target weed

Melaleuca quinquenervia, otherwise known as the paper-bark tree, is a member of the Myrtaceae family, sub-family Leptospermoidae (Serbesoff-King, 2003). This tall evergreen tree historically occupies tropical wetland sites throughout its native range along the eastern coast of Australia (Kauffman and Smouse, 2001). It was introduced into South Florida in 1886 originally for sale as an ornamental, but later was used for erosion control, as a forestry crop, and as an agricultural windrow plant (Dray et al., 2006). A 1998 study estimated that *M. quinquenervia* had invaded approximately 400,000 ha in the State of Florida (LaRoche, 1998). Studies have shown that *M. quinquenervia* infestations can alter the abundance of native plant species, wildlife habitats, and ecosystem nutrient storages (Serbesoff-King, 2003; Martin et al., 2009).

2.2. Biological control agents

Currently the growth and reproductive capacities of *M. quinquenervia* are being suppressed by two intentionally introduced, specialized insect herbivores, *Oxyops vitiosa* Pascoe (Coleoptera: Curculionidae) and *Boreioglycaspis melaleucae* Moore (Hemiptera: Psyllidae) (Tipping et al., 2008b). Two other species have only recently been released so information on their impact is unavailable. *Oxyops vitiosa* larvae and adults feed on buds and newly flushing leaves (Balciunas et al., 1994). The feeding activity of the larvae is the most damaging to the plant and causes long, window-like scars on leaves (Purcell and Balciunas, 1994). Larvae are covered in a thick viscous coating consisting of essential oils sequestered from *M. quinquenervia* which provides an effective anti-predator defense (Wheeler et al., 2002). *Boreioglycaspis melaleucae* adults and nymphs feed on plant phloem (Purcell et al., 1997; Wineriter et al., 2003). Both *O. vitiosa* and *B. melaleucae* have established and spread throughout South Florida (Center et al., 2006; Tipping et al., 2008b).

2.3. Site description

The study site was located in the Belle Meade Tract of the Picayune Strand State Forest in Collier County, Florida. This area consists of nearly level, poorly drained, low fertility soils which are loamy, siliceous, hyperthermic Arenic Glossoqualfs. The soil series is Pineda-Boca-Hallandale which is characterized by moderately to poorly drained sands which overlie limestone bedrock to a depth of approximately 1.4 m (USDA, 1998). The water table fluctuates annually between greater than 15 cm below the soil surface to approximately 25 cm above. The area has a distinct wet season from about July to December and a dry season from January to June. Average annual rainfall in this region is approximately 1.36 m (SERC, 2007). Historically, the vegetation in this area was a mixed *T. distichum*–*P. elliottii* forest with a hardwood under-story. Over the past several decades, many areas in this landscape have been invaded by *M. quinquenervia* and are now comprised of sparse populations of mature trees with dense understories of saplings that can exceed densities of 100 plants per square meter.

2.4. Experimental design

In order to assure the proper assignment of treatment causality in experiments several fundamental assumptions must be met including the random assignment of treatments across experimental units and treatment replication (Beyers, 1998). The most rigorous field studies have randomly assigned, replicated experimental treatments. Often, however, land managers manipulate natural areas to restore function, provide habitat, or mitigate anthropogenic disturbance without regard for experimental design. As a result, large tracts of land are treated as needed or as resources allow. The resulting landscapes are complex and provide a statistical challenge to empirical studies. Despite this, evaluating large-scale field treatments can provide unique opportunities and should be pursued to gain insight on the outcomes of adaptive management of ecosystems.

The current study evaluated the results of a multi-agency, integrated management strategy that has taken place over the course of several decades. As large tracts of the native forest became in-