Forest Ecology and Management 376 (2016) 126–134

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Alternative field fertilization techniques to promote restoration of leguminous *Acacia koa* on contrasting tropical sites

Kyle M. Earnshaw[a], Thomas W. Baribault[b], Douglass F. Jacobs[a,*]

[a] *Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907-2061, USA*
[b] *Forest Solutions, Inc., Paauilo, HI 96776, USA*

ARTICLE INFO

Article history:
Received 13 April 2016
Received in revised form 4 June 2016
Accepted 6 June 2016
Available online 13 June 2016

Keywords:
Controlled-release fertilizer
Nitrogen
Nutrient management
Outplanting
Phosphorus
Tropical forest restoration

ABSTRACT

Field fertilization can promote early growth and survival of planted trees on degraded pastures and agricultural lands where low soil fertility and high herbaceous competition inhibit regeneration success. Controlled-release fertilizers (CRF) may improve the effectiveness of fertilization relative to that of immediately available fertilizers (IAF) because CRF gradually release nutrients directly to the root zone, thereby limiting nutrient losses. Despite past research in boreal and temperate landscapes, few studies have tested the efficacy of similar applications in tropical systems where year-round high temperatures can increase release rates of CRF and intensity of competing vegetation. On two contrasting sites on the Island of Hawaii, USA, we evaluated early growth and survival responses of koa (*Acacia koa* Gray), a fast-growing legume, using ten treatments: a control, four IAF formulations, and five rates of polymer-coated CRF (15N-9P-12K; 15–75 g). At Pahala, a productive site, we detected no significant growth, survival, or foliar nitrogen (N) or phosphorous (P) responses to the fertilizer treatments. At Volcano, a rockier and cooler site on younger soil, height increased by 36–49% for the highest performing CRF and IAF relative to the control; diameter likewise increased by 55–92%. Growth responses appeared to be a result of P fertilization rather than N. The highest performing IAF had a reduced survival rate relative to the lowest CRF (46% vs. 83%). Although total nutrient application rates were much lower for CRF, our results suggest that on tropical restoration sites, CRF may promote seedling performance at least equally to that of IAF. There is a need to more carefully evaluate the effects of site-specific interactions that may determine field fertilizer responses, across a range of genera and functional groups.

1. Introduction

Newly planted forest tree seedlings can benefit from field fertilization in both restoration and plantation settings. Fertilization may amplify the effects of other silvicultural inputs, such as herbaceous control (Sloan and Jacobs, 2013) and site preparation, leading to increased early growth and survival. Positive outcomes from field fertilization are dependent on climate, soils, and the species fertilized and responses have been mixed in temperate (Bendfeldt et al., 2001; Fox et al., 2007; Jacobs et al., 2005), boreal (Brand, 1991; Sloan and Jacobs, 2013; Sloan et al., 2016), and tropical regions (Lawrence, 2003; Schönau and Herbert, 1989).

Fertilizer dosage and chemical formulation influence the effectiveness of the application. Growth of forest trees is most commonly limited by nitrogen (N) or phosphorous (P). Fertilizer that provides P on an N-limited site, or vice versa, may produce negligible results, as in the case many *Eucalyptus* spp. (Schönau and Herbert, 1989), where response to a given nutrient is species and site specific. Similar effects occur in loblolly pine (*Pinus taeda* L.), in which P is limiting and an effective addition at planting on wet sites in the southern USA but ineffective on many other sites where both N and P are limiting (Fox et al., 2007). Similar effects occur in N-fixing seedlings and mature trees (Binkley et al., 2003; Otsamo et al., 1995; Scowcroft and Silva, 2005; Scowcroft et al., 2007), but a lack of correlation between available soil P resources and growth of legumes in Costa Rica suggests inconsistency in responses across species (Baribault et al., 2012). *Acacia* spp., for example, differ in their preference for nitrate versus ammonium and nodulation response to P fertilization (Sun et al., 1992; Pfautsch et al., 2009), suggesting the importance of species-specific fertilization applications.

In addition to the importance of dosage and formulation, fertilizer type can also determine the effectiveness of the application. The two most common fertilizer types for field plantings are controlled-release fertilizers (CRF) and immediately available

---

* Corresponding author.
E-mail address: djacobs@purdue.edu (D.F. Jacobs).

http://dx.doi.org/10.1016/j.foreco.2016.06.012
0378-1127/

fertilizers (IAF). CRF provide a constant source of nutrition to outplanted seedlings over an extended period (Jacobs et al., 2005), determined by the release rate of a given CRF, which can vary from 3 to 18 months. With polymer-coated CRF, water diffuses through a semi-permeable membrane and releases nutrients (Goertz, 1993). Although water is the initial conduit for nutrient release, soil temperature is the mechanism controlling release rates; higher soil temperatures result in faster release rates in polymer-coated CRF (Kochba et al., 1990). This system may result in an efficient delivery system of nutrients to outplanted seedlings compared to IAF, with reduced nutrient loss out of the system or to competing vegetation (Sloan and Jacobs, 2013). Recent work (Sloan et al., 2016), however, suggests that a high proportion of applied N in both CRF and IAF is lost from the system and planted trees recover only a small proportion. Nevertheless, CRF may maintain or increase growth and survival of planted trees at lower total fertilization rates than IAF (Sloan et al., 2016), which is subject to high rates of nutrient loss through volatilization, leaching, and non-target uptake by competing vegetation following broadcast application (Chang et al., 1996; Imo and Timmer, 1998; Ramsey et al., 2003; Sloan and Jacobs, 2013; Staples et al., 1999). Leached N and P from broadcast fertilizers can also contaminate local water supplies (Binkley et al., 1999; Foley et al., 2005).

Tropical forests have experienced high rates of deforestation (ITTO, 2002), affecting the world's poor particularly hard (Lamb et al., 2005). Reforestation and restoration programs on degraded tropical landscapes can help to alleviate these losses, and silvicultural advances may help to ensure the effectiveness of these efforts. Despite positive research results using CRF in temperate and boreal regions, these fertilizers have not been tested extensively in the tropics where warm temperatures persist year-round, potentially accelerating release rates and confounding ability to transfer fertilizer prescriptions from other biomes.

Hawaii, in particular, has experienced high rates of forest degradation and deforestation, having lost more than half of its native forest to non-native systems (Gon et al., 2006). As such, Hawaii has been proposed as a laboratory for the implementation of innovations in restoration technologies (Friday et al., 2015). Restoration plantings usually rely on koa (*Acacia koa* Gray), one of two canopy level trees across most climate types in Hawaii (Gagne and Cuddihy, 1990), which has great cultural (Whistler, 2009) and economic (Scowcroft et al., 2010) significance and status as one of the most important native trees to Hawaii. After centuries of degradation following the introduction of goats (*Capra hircus*) in 1778, domestic sheep (*Ovis aries*) in 1791, and cattle (*Bos taurus*) in 1793 (Ziegler, 2002) and extraction of timber from native forests (Woodcock, 2003), the value of koa has increased and put additional pressure on naturally regenerated koa stands to satisfy demand for furniture and musical instruments, among other uses (Friday, 2011; Scowcroft et al., 2010; Yanagida et al., 2004). Efforts to reforest upper-elevation areas are further motivated by the importance of providing habitat to endangered birds threatened by the spread of avian malaria (*Plasmodium relictum*) as the climate warms (Rock et al., 2012).

Koa's extensive native range provides a setting where fertilizers can be tested on contrasting sites to identify the advantages of dosages, formulations, and delivery mechanisms. Koa is a shade intolerant, pioneer species (Walters and Bartholomew, 1984; Walters and Bartholomew, 1990; Baker et al., 2009) that occupies a dominant canopy position in forests. Koa uses a heteroblastic growth habit to regenerate in both open fields and large canopy gaps, in which younger true leaves maximize light capture while mature, horizontally oriented phyllodes improve drought tolerance and maintain maximum photosynthetic rates (Craven et al., 2010; Pasquet-Kok et al., 2010). It grows in forests where elevation ranges from around sea level to 2000 masl (Gagne and Cuddihy, 1990), mean annual minimum temperature ranges from less than −1 °C to over 4 °C, and climate types are categorized from xeric to wet (Baker et al., 2009). Hawaiian soils across koa's range are diverse. Soil age and weathering of volcanic soils create a succession of nutrient limitations from N on younger soils to P on older soils, a pantropical trend (Harrington et al., 2001; Vitousek and Farrington, 1997). On a mix of young soils from 2 to 15 ka, however, Pearson and Vitousek (2001) found that annual growth rates of 6- to 20-year-old koa did not increase with N fertilization, instead arguing that P likely functioned as the primary limiting nutrient. This contrasted with results of Vitousek and Farrington (1997), however, who found that N limited growth of *Metrosideros polymorpha* Gaud. on young soils and P, on older soils. The discrepancy in findings may have been because *M. polymorpha* is not an N-fixer, but koa is, or because the studied koa were already well established on the site. These results indicate that N-fixation (Dreyfus et al., 1987; Parrotta, 1992; Miyasaka et al., 1993; Pearson and Vitousek, 2001) may be sufficient to provide koa with N, but the findings do not preclude the possibility that seedling N fertilization (Davis et al., 2011; Dumroese et al., 2011, 2009) may prove useful on degraded sites targeted for forest restoration. These results also suggest that P fertilization may be more important than N fertilization. Furthermore, as a result of the diversity of climate types where koa dominates the canopy, optimal fertilization prescriptions for koa plantations likely vary depending on plantation goals, economics, soil fertility, temperature and annual rainfall.

Thus, we installed experiments at two contrasting sites in Hawaii. We asked the following three questions. First, how would a wide variety of fertilization techniques affect early growth and survival of planted koa seedlings? We hypothesized that increasing fertilization would promote growth, until the highest application rates where phytotoxicity would be observed. We also hypothesized that survival would increase with CRF application relative to IAF because CRF provide a more consistent supply of nutrients. Second, can CRF maintain or improve growth and survival relative to IAF in spite of lower overall amount of nutrients delivered? We hypothesized that CRF would maintain growth increases of IAF relative to the control despite lower overall application rates. Finally, will response to fertilization be consistent across two contrasting sites? We hypothesized that growth and survival would be highest at Pahala, but that fertilization would be more important at Volcano because of its relatively lower site quality.

2. Methods

2.1. Site description

Trials were located near Pahala (19.2214°N, 155.4969°W, 616 masl) and Volcano (19.4757°N, 155.3320°W, 1543 masl), Hawaii on land managed by Kamehameha Schools. The Pahala site was used for cultivation of sugar cane through the early 1990s, while the Volcano site was used as pasture through 2002; both sites were in fallow grass cover for a least a decade prior to planting koa. The locations were selected to minimize differences in slope, with both sites at less than 5% slope overall. The Pahala and Volcano sites receive similar amounts of annual rainfall. For the first year of the study during which Pahala was measured, Pahala received 728 mm according to NOAA weather station, Pahala Mauka (19.204°N, 155.480°W; NCDC, 2016). During the same year, a RAWS station at Keaumo (19.474°N, 155.359°W), close to the Volcano site, received 734 mm of rainfall (RAWS, 2016). Total precipitation during the measurement period from January 2013 to August 2014 at Volcano was 1730 mm. Mean annual temperature is lower at Volcano (13.5 °C) than at Pahala