Ecological Economics 146 (2018) 125–135

Contents lists available at ScienceDirect

Ecological Economics

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

Analysis

Joint Management of an Interconnected Coastal Aquifer and Invasive Tree

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ARTICLE INFO

Keywords:
Prosopis pallida
Kiawe
Groundwater management
Invasive species
Kīholo

ABSTRACT

Kiawe (*Prosopis pallida*), a mesquite tree considered invasive in many parts of the world including Hawai'i, has been shown to reduce regional groundwater levels via deep taproots. In areas where aquifers are primary sources of fresh water, kiawe control has the potential to be an integral component of water management planning. We develop an analytical dynamic framework for the joint management of kiawe and groundwater, and show that optimal water management depends on expected kiawe damages, while optimal kiawe removal depends on groundwater scarcity and removal cost. Using data from the Kīholo aquifer on the west coast of Hawai'i Island, we solve for joint management decisions with corresponding parameters related to kiawe damage and water scarcity. With 1.5% water demand growth, Kiawe should be removed if the removal cost is below $1884/ha. Our numerical results indicate that kiawe damage is nonlinear in the rate of water demand growth. The damage costs can be attributed to three main factors. When demand growth is low, kiawe damage is driven by a higher water extraction cost. For moderate growth, the effect is compounded by anticipated future scarcity. Damage is amplified by a backstop cost effect when the growth rate is high.

1. Introduction

Kiawe (*Prosopis pallida*) is a nonnative tree introduced to Hawai'i in the early nineteenth century that can potentially reduce coastal groundwater quality by providing nitrogen-rich organic material for leaching, as well as reduce regional groundwater levels via deep taproots (Richmond and Mueller-Dombois, 1972; Dudley et al., 2014). Kiawe can be found in both coastal wetlands and upland ecosystems, covering over 60,000 ha of the state's total land area (Gon et al., 2006). The introduction of kiawe into leeward coastal areas of Hawai'i Island has been shown to increase groundwater uptake, altering local hydrological processes including possible reductions in submarine groundwater discharge (Dudley et al., 2014).

The objective of this paper is to help extend the principles of resource economics to deal with the joint management of interdependent resources, and provide an illustrative case from Hawai'i, where the groundwater uptake of an invasive species detracts from the aquifer stock. Building off of a simple model developed in Burnett et al. (2014), we employ a standard approach of maximizing the present value (PV) of net benefits generated by the groundwater aquifer, and specify the optimal steady state stock level of both stock of water and invasive species, while characterizing the path of optimal resource management leading to those steady states. The difference in NPV's between the case with and without management is one approach to characterizing damages from the invasive species (or alternatively, the benefits of invasive species management).

Prosopis pallida was introduced from South America to areas in Asia, Africa, and Oceania during the early nineteenth century. The first kiawe in Hawai'i was planted in 1828 on the island of O'ahu (Wilcox, 1910; Birkett, 2007). By the 1890s, kiawe was widely recognized for its use as cattle feed and fuel wood. Consequently, kiawe spread rapidly throughout the dry leeward lowland areas of O'ahu and the other main islands of Hawai'i, its spread directly linked to its use as feed for the growing cattle industry in Hawai'i.

A characteristic of kiawe's invasive nature is its rapid growth, described as reaching full height of 6-8 m within three or four years (Hall, 1904). The tree reaches maximum height and productivity in riparian zones with access to shallow groundwater (Schade et al., 2003). Kiawe are described as phreatophytes (“groundwater-loving plants”), referring to their root system, which is capable of accessing relatively deep groundwater sources. This deep taproot system has been implicated in lowering groundwater tables in Hawai'i (Richmond and Mueller-Dombois, 1972). On Kaho'olawe, Stearns (1940) found that a decline in the groundwater level coincided with the spread of kiawe. Zones (1961) speculated that kiawe transpiration was responsible for an observed daily rise and fall of the groundwater level on O'ahu (Pasiecznik et al., 2001). Large stands of kiawe remain on all the main islands of Hawai'i, particularly where development is limited and cattle ranching

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http://dx.doi.org/10.1016/j.ecolecon.2017.10.011
Received 1 July 2017; Received in revised form 2 October 2017; Accepted 7 October 2017

continues.

Decision rules for the economically efficient allocation of groundwater were first developed almost half a century ago (Burt, 1967; Brown and Deacon, 1972). More recent efforts have refined the hydrogeological aspects of the management framework, developed instruments for implementing optimal extraction, and considered the welfare implications of various management strategies (Krulce et al., 1997; Koundouri, 2004; Brozović et al., 2010). Few, however, have considered the simultaneous management of natural resources that are interconnected with the aquifer of interest. Those that have modeled resource interdependency (both within and outside the groundwater literature) typically focused on management of a single resource, taking harvest from the adjacent resource as exogenous, e.g., shrimp farms and offshore fisheries (Barbier et al., 2002) and groundwater and nearshore species such as seaweed (Duarte et al., 2010).

Efficient joint management of water and invasive species will recognize linkages between these resources (Burnett et al., 2007; Funk et al., 2014). Managing invasive species can have direct or indirect benefits on environmental outcomes such as water quality (Connelly et al., 2007), air quality (Jones et al., 2006), and landscape flammability (Wada et al., 2017). There are several examples of invasive species with well-measured effects on linked water resources (Turpie et al., 2008, Van Wilgen et al., 2011). An example of a plant invader with well-studied implications to water is salt cedar (*Tamarix* spp.), which is found in floodplains throughout in the southwestern United States and consumes 3000–4600 m^3/ha/year more water than does the native vegetation that it replaces (Zavaleta, 2000). Another plant species, yellow starthistle (*Centaurea solstitialis*), results in water losses due to its late summer drawdown of soil moisture amounting to as much as $75 million each year in the economically important agricultural region surrounding the Sacramento River (Gerlach, 2004). In the model presented here, management decisions consider direct tradeoffs both between resources (groundwater and kiawe) and over time. In an application near Kīholo Bay on the island of Hawai'i, a basic groundwater management model was modified to include water uptake by kiawe.

Our study site is located along the Kona coast near Kīholo Bay on Hawai'i Island. Kiawe's long taproots extend into the ground through cracks in the rock. Kīholo Bay receives considerable shallow submarine groundwater discharge near its shoreline via freshwater flow from the upper watershed (Peterson et al., 2009). Dudley et al. (2014) documented kiawe's access to groundwater along this coast and found that kiawe stands were able to successfully access and utilize groundwater and subsequently transpire substantially (~80%) more water than was supplied via rainfall. Results support the idea that the presence of kiawe has altered the hydrological processes of this region, which is now characterized by a negative water budget through groundwater uptake and continuous transpiration. We use this data to parameterize an illustrative joint management model of groundwater and kiawe, where the stock of groundwater provides benefit, and the stock of kiawe affects this benefit directly via groundwater uptake through its taproots.

2. Materials and Methods

2.1. Aquifer Dynamics

We assume a single-cell coastal aquifer (Fig. 1), where the head level (h), or the distance between mean sea level and the top of the freshwater lens, is proportional to the volume of stored groundwater; γ is a volume-height conversion factor. The head level changes over time according to recharge (R), natural leakage along the aquifer boundary (L), extraction (q), and uptake (u) by overlying kiawe trees (K) as shown in Eq. (1):

$$\dot{h}_t = \gamma [R - L(h_t) - q_t - u(K_t)] \tag{1}$$

Recharge (R), or the quantity of freshwater that replenishes the aquifer annually, is taken as exogenous and constant in our model, but more generally depends on factors such as precipitation patterns, characteristics of adjacent water bodies, and the types of land cover overlying the recharge zone. Leakage is an increasing and convex function of head (i.e., $L'(h_t) > 0$ and $L''(h_t) \le 0$). A higher head level generates greater pressure along the aquifer boundary, ultimately resulting in more leakage at the coast in the form of submarine groundwater discharge and/or springs.

2.2. Kiawe Dynamics

Kiawe spreads according to the stock-dependent net-growth function F. We assume that the growth represents the spread of kiawe over space, and in the application the stock (K) is measured in units of area (e.g., hectares). Kiawe can also be removed or exterminated at rate x. Thus, the change in kiawe stock in any period is determined jointly by its natural growth rate and management effort (Eq. (2)).

$$\dot{K}_t = F(K_t) - x_t \tag{2}$$

2.3. Benefits

The benefit of water use is measured as the area under the inverse demand curve (D^{-1}) as shown in Eq. (3):

$$B_t = \int_0^{q_t+b_t} D^{-1}(y_t, t)dy \tag{3}$$

A backstop resource (b), desalination, can be used to supplement or replace groundwater extraction.[1] We assume that the sources are indistinguishable in terms of quality and therefore have the potential to generate identical marginal benefits at a given level of consumption. The inverse demand is also directly a function of t to allow for the possibility that demand for water is rising over time due to population and/or per capita income growth.

2.4. Costs

The cost of groundwater extraction is a decreasing and convex function of the head level $c_q(h)$. The more depleted the aquifer, the more energy is required to lift groundwater over a longer distance to the ground surface. We assume that desalinated brackish water can be obtained at a constant unit cost c_b.

The unit cost of tree removal (c_x) is assumed to be constant and is comprised of chemical, mechanical and/or labor costs. We assume that once a tree is removed, no additional maintenance is required. The total cost of obtaining water and managing kiawe in period-t is shown in Eq. (4):

$$C_t = c_q(h_t)q_t + c_b b_t + c_x x_t \tag{4}$$

2.5. Optimization Problem

The dynamic optimization problem faced by the resource manager is to choose groundwater extraction, desalination, and kiawe removal

[1] The assumption that the planner can perfectly substitute between the aquifer and desalination is meant to keep the model analytically tractable but could be viewed as overly simplistic from a practical standpoint; a desalination purchase contract is often required for a set period, which would result in a horizontal or stepped (rather than smoothly inclining) production trajectory once desalination comes online. The problem of optimal desalination expansion (e.g. Saif and Almansoori, 2014) is itself, i.e. without being coupled with invasive species management, complex. Although outside the scope of the current study, the ideal joint management model would incorporate a suite of possible groundwater substitutes including desalination (Roumasset and Wada, 2010; Beh et al., 2014), and the management problem would entail optimizing both the use of groundwater and the order of supply side alternatives, while accounting for invasive species interactions.