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Original Research Article

Dynamical study of native and exotic competing populations: Effects of habitat destruction

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ABSTRACT

In this paper, mathematical models have been studied to investigate the survival of native species and exotic species when the hydrological conditions and habitat characteristics both are changing for constant input of rainfall. The local and global stability analysis of the equilibrium points is carried out. From the analysis it is concluded that if habitat characteristic is favourable for native species then equilibrium level of native species increase and equilibrium level of exotic species decrease due to increase of constant introduction of rainfall. If habitat characteristic is favourable for exotic species then equilibrium level of exotic species increase and equilibrium level of native species decrease due to increase of constant introduction of rainfall. It is also observed that the equilibrium level of native species increases if the habitat destruction is less under the favourable habitat characteristic but on the contrary the equilibrium level of exotic species increases if the habitat destruction is more even when the habitat characteristic is not favourable to exotic species. Finally the numerical simulation is also carried out to support the analytical results.

1. Introduction

Habitat loss and destruction can occur both naturally and through anthropogenic causes. Events leading to natural habitat loss include climate change, catastrophic events such as volcanic explosions and through the interactions of invasive and non-invasive species.

Species that are able to thrive and reproduce in a new environment is called alien, nonnative, non-indigenous, introduced or invasive. Exotic plants are any plants that do not naturally grow in an area. They find their way to an ecosystem from a completely separate area, often via animals or human intervention.

The persistence of natural population faces three challenges: habitat destruction, climatic change and biological invasion. Among these challenges, habitat destruction has been suggested to be the foremost cause of species extinction (Roser and Mainka, 2002; Fahrig, 1997; Pimm and Raven, 2000). Consequently, understanding the dynamics of extinction, as well as species response to the habitat destruction is crucial for conservation planning and management (Klausmeier, 1998; Tilman et al., 1994, 1997; Ceballos and Ehrlich, 2002; Bascompte, 2003; Ovaskainen et al., 2002; Ovaskainen and Hanski, 2001; Ehrlich and Ehrlich, 1981; Benton, 2003).

At present it is important to study the impact of change in habitat characteristics due to its destruction on the distribution and interaction of species. Many authors have studied effect of changing habitat on survival of species (Shukla et al., 1996a,b; Fatma Bayramoglu Rizaner et al., 2012; Feng-Bin Wang, 2010; Shukla et al., 1996a,b; Ling-ling Chen and Cang Hui, 2009; Misra et al., 2000, 2005) and effect of exotic species on native species (Joydeep Bhattacharjee et al., 2008; Misra et al., 2012; Pamela et al., 2003, 2005; Beauschamp et al., 2005). It has been noted that the hydrology of southwestern United States rivers has led to a decline in native (Populus deltoides) species. Areas historically dominated by native have been replaced by invasive exotic (Saltcedar chinensis). Restoration of historic hydrology through periodic flooding of riparian areas has been a means of restoring native species. However, due to similarity in germination requirements of natives and exotics, flooding may create an unwanted increase in the number of exotic seedlings.

Joydeep Bhattacharjee et al. (2008) have pointed out in their study that if favourable germination conditions are established for native in floodplains, exotic seedlings that cogerminate could be outcompeted by native seedlings.

An extensive work has been carried out so far related to the mathematical modelling of single as well as two competing species

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system (Fatma Bayramoglu Rizaner et al., 2012; Feng-Bin Wang, 2010; Joydeep Bhattacharjee et al., 2008; Zhipeng Qiu, 2011). However not much work has been done regarding the effect of habitat destruction on the growth dynamics of single species and two species competing population using mathematical models.

In view of the above the main purpose of this paper is to construct a general model to study the effect of exotic species on competing native species under the degrading habitat due to changing habitat characteristic.

2. Biological background

Cottonwood is a fast-growing tree which reaches 80–l00 feet in height and 3–4 feet in diameter. It is a relatively short-lived tree, seldom surviving for more than 80 years. Cottonwood makes its best growth on moist, well-drained, fine sandy loams or silt loams. Coarse sands and heavy clay soils are not satisfactory. It has been found to be relatively tolerant of drier sites as shown by survival and growth of trees planted on strip mine spoils. Cottonwood is resistant to flood damage and usually tolerates a soil pH range of 4.5–8.0. Eastern cottonwood is distributed throughout the East and Midwest.

Saltcedar is a tree native to Eurasia. Saltcedar has naturalized and become a major invasive plant species in parts of the world, such as in the South Western United States and Desert Region of California, consuming large amounts of groundwater in riparian and oases habitats. Saltcedar is an invasive species, first brought to the U.S. in 1837 by nurseries for use as an ornamental and to prevent erosion in arid regions and planted to stabilize stream bank erosion and used to provide windbreaks and shade. Current estimates suggest that over 1.5 million acres are occupied by saltcedar.

Saltcedar characteristics promote its invasive ability to compete in an environment where soil, water, and climate can be harsh. Soils are often shallow with little organic matter. Saltcedar has the capability of altering the environment to reduce competitors.

It is commonly believed that saltcedar disrupts the structure and stability of North American native plant communities and degrades native wildlife habitat, by outcompeting and replacing native plant species, salinizing soils, monopolizing limited sources of moisture, and increasing the frequency, intensity and effect of fires and floods. While it has been shown that individual plants may not consume larger quantities of water than native species (Anderson, 1996), it has also been shown that large dense stands of saltcedar do consume more water than equivalent stands of native cottonwoods. There is an active and ongoing debate as to when the saltcedar can out-compete native plants, and if it is actively displacing native plants or it just taking advantage of disturbance by removal of natives by humans and changes in flood regimes (Stromberg, 1998). Research on competition between saltcedar seedlings and co-occurring native trees has found that the seedlings are not competitive over a range of environments (Gilbert et al., 2000), however stands of mature trees effectively prevent native species establishment in the understory, due to low light, elevated salinity, and possibly changes to the soil biota (Taylor, 1998). Thus, anthropogenic activities that preferentially favour saltcedar (such as changes to flooding regimes) are associated with infestation (Horton et al., 2001). To date, Saltcedar has taken over large sections of riparian ecosystems in the western United States that were once home to native cottonwoods and willows (Zamora-Arroyo, 2001; Stromberg, 1998), and are projected by some to spread well beyond the current range.

3. Basic assumptions and mathematical model

Let $E(t)$ denotes the measure of hydrological conditions determined by rainfall, $H(t)$ denotes the measure of habitat characteristics such as soil, temperature, biodiversity, $N_1(t)$ denotes the density of native species and $N_2(t)$ denotes the density of exotic species. We assume that c_1 is loss of natural hydrological condition (amount of rainfall) due to runoff and infiltration of rain water and c_2 is loss in natural habitat characteristic. a_2 and b_2 are intraspecific competition of native species and exotic species respectively. $\gamma (0 < \gamma < 1)$ is the fraction of amount of rainfall water retained in the habitat. Q_0 is the constant introduction of rainfall. Q_1 is the natural constant introduction of habitat. $a_1(H)$ and $b_1(H)$ are specific growth rate coefficient of the native species and exotic species dependent on habitat respectively. $a_3(H)$ is the specific decay rate coefficient of the native species due to interspecific competition coefficients with exotic species dependent on habitat. $b_3(H)$ is the specific decay rate coefficient of the exotic species due to interspecific competition coefficient with native species dependent on habitat. D is the degree of habitat destruction due to human actions and man-made projects. In the model, the hydrological conditions and habitat characteristics are considered to be the forcing variables which are driving the underlying system of two competing populations.

In view of above, the resultant system dynamics is governed by the following system of differential equations:

Model 1(With exotic species)

$$\frac{dE}{dt} = Q_0 - c_1 E \tag{1}$$

$$\frac{dH}{dt} = Q_1(1 - D) - c_2 H + \gamma c_1 E \tag{2}$$

$$\frac{dN_1}{dt} = a_1(H)N_1 - a_1 N_1^2 - a_3(H)N_1 N_2 \tag{3}$$

$$\frac{dN_2}{dt} = b_1(H)N_2 - b_2 N_2^2 - b_3(H)N_1 N_2 \tag{4}$$

With initial conditions as $E(0) \geq 0, H(0) \geq 0, N_1(0) \geq 0$ and $N_2(0) \geq 0$. Where $a_2, b_2, c_1, c_2, \gamma, Q_0, Q_1, D,\ 0 < D < 1$ are positive constants and $a_1(H), a_3(H), b_1(H), b_3(H)$ are non-negative continuous functions for $H \geq 0$.

In the absence of exotic species the above system (1)–(4) is governed by the following system of differential equations:

Model 2 (without exotic species)

$$\frac{dE}{dt} = Q_0 - c_1 E \tag{5}$$

$$\frac{dH}{dt} = Q_1(1 - D) - c_2 H + \gamma c_1 E \tag{6}$$

$$\frac{dN_1}{dt} = a_1(H)N_1 - u_2 N_1^2 \tag{7}$$

With initial conditions as $E(0) \geq 0, H(0) \geq 0$ and $N_1(0) \geq 0$.

Case A Habitat characteristic is favourable for native species

The function $a_1(H)$ is the specific growth rate coefficient of the native species and it increases as habitat characteristics become more conducive. We assume

$$a_1(0) = a_{10}, a_1'(H) > 0 \quad \text{for } H \geq 0 \text{ and } a_{10} \leq a_1(H) \tag{8a}$$

The function $a_3(H)$ is the specific decay rate coefficient of the native species due to interspecific competition coefficients with exotic species and it decreases as habitat characteristics become more conducive. We assume

$$a_3(0) = a_{30},\ a_3'(H) < 0 \quad \text{for} H \geq 0 \,\text{and}\, a_3(H) \leq a_{30} \tag{8b}$$

The function $b_1(H)$ is the specific growth rate coefficient of the exotic species and it decreases as habitat characteristics become