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The salinity gradient influences on the inundation tolerance thresholds of mangrove forests

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ABSTRACT

In order to test whether salinity gradient influences inundation tolerance thresholds of mangrove forests, we used validated hydraulic and dispersion model to characterize these two abiotic environmental factors on four riparian mangrove forests, namely Wazwei, Zhuwei, Guandu, and Shezi, with only one mangrove species (*Kandelia obovata*) in the Tanshui River system. The results showed that the inundations of the highest and the lowest elevations for mangrove growth both increase while salinity decreases. In other words, mangrove inundation tolerance is found to be inversely dependent on salinity concentration. The inundations of *K. obovata* growth were 0.35–22.11% (0.08–5.31 h/day), 1.82–24.99% (0.44–6.00 h/day), 3.75–39.99% (0.90–9.60 h/day), and 5.73–38.25% (1.38–9.18 h/day) on the Wazwei, Zhuwei, Guandu, and Shezi wetlands respectively due to different annual mean salinity (28.57, 21.30, 11.98 and 10.01 ppt for the Wazwei, Zhuwei, Guandu, and Shezi wetlands respectively). Mangrove forests with lower salinity condition, such as the Guandu wetland, have higher potential to invade into river and to occupy flow area, and thus damage flood prevention project. These mangrove forests need not only protection projects but also further management projects, such as regular artificial forest thinning. In addition, under consideration of salinity and inundation frequency alteration, the *K. obovata* forests on the Zhuwei wetland and the Guandu wetland would vanish around 63% and 35% by 2100, because landward migration would be limited by levees. The difference of mangrove loss rate is due to different local topography. A binomial distribution representing the relationship of annual mean salinity and inundation frequency was developed for evaluating appropriate hydrological regimes of mangrove growth as well. It is also suggested to guide a suitable restoration project and predict mangrove forest loss due to sea level rise.

1. Introduction

Mangrove forests have a broad range of biological, economic, scientific, environmental, aesthetic, and social benefits (Blasco et al., 1996; Mitsch et al., 2005). They covered about 1880 ha of sheltered tropical coastlines throughout the world in 1980, but almost 20% of the mangrove forests have since been lost due to clearing for aquaculture, urbanization and timber products (Alongi, 2002; FAO, 2007). Even though the number of mangrove projects is increasing worldwide, most of them have failed completely or have failed to achieve their original goals (Lewis, 2005).

In China, the mangrove survival rate in most reforestation projects was less than 20% (Chen et al., 2003; Lin et al., 2005a). Lin et al. (2005a) pointed out that mangrove seedlings were planted in inappropriate areas, where inundation frequency exceeded the tolerance range of mangrove seedlings, resulting in low survival rate of these projects. Mangroves can grow and thrive in a variety of coastal and riparian environments if the hydrological conditions are suitable (Ellison, 2000). However, mudflats in front of existing or previous mangrove stands that are often proposed as reforestation sites do not support mangrove growth (Lewis, 2005).

Many studies note that mangrove areas are limited to certain substrate elevations relative to characteristic tidal level, inundation time, or inundation frequency (e.g., Watson, 1928; Clarke and

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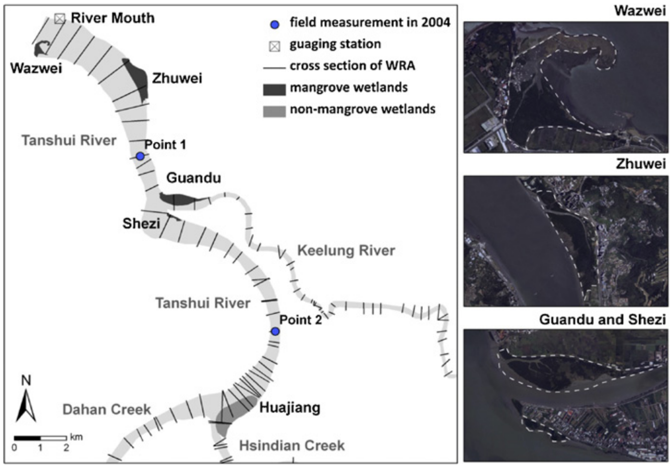

Fig. 1. Map of the study area. The tidal reach of the Tanshui River system includes four riparian mangrove wetlands – Wazwei, Zhuwei, Guandu, and Shezi. The distance from river mouth to the junction with the Keelung River is about 8.6 km.

Hannon, 1967; Lear and Turner, 1977; Stephen, 1984; Detweiler et al., 1975; Branch and Grindle, 1979; Kenneally, 1982; Hutchings and Saenger, 1987; Kjerfve, 1990; Ellison, 1993; Ellison and Farnsworth, 1996; Cahoon and Lynch, 1997; Ellison, 2000; McKee and Faulkner, 2000). However, most of them showed totally different thresholds. For example, Kjerfve (1990) claimed that mangrove forests stand above bankfull where they are inundated between 1% and 9% of the time in the Klong Ngao creek, Thailand. Zhang et al. (1997) showed that inundation frequency from 2.9 to 47.5% is suitable for mangrove growth based on their survey in China. Few studies focus on the influences of salinity gradient on mangrove inundation tolerance.

The aim of this study is to critically examine the influence of salinity on the inundation tolerance of mangrove forests and offer a method to forecast mangrove habitat shift under alteration of salinity and inundation frequency. The annual mean salinity and inundation frequency curves on four different riparian mangrove wetlands were calculated based on hydraulic and dispersion model simulation results, followed by an assessment of inundation tolerance in mangrove stands. This study also develops a formula to estimate inundation tolerance of mangroves under different salinity conditions and present a forecast of mangrove forest area changes up to 2100.

2. Materials and methods

2.1. Study area

There are four major mangrove wetlands within our study area of the Tanshui River system in northern Taiwan, namely Wazwei, Zhuwei, Guandu, and Shezi wetlands (Fig. 1). Only one mangrove species, *Kandelia obovata*, grows here due to cold temperatures (Sheue et al., 2003). These habitats comprise the largest population of *K. obovata* in the northern hemisphere (Hsu, 2002) and represent the species' northernmost geographical position (Lee and Yeh, 2009).

The Tanshui River system consists of three main tributaries: Dahan Creek, Hsindian Creek and Keelung River. The mainstream is approximately 158 km long with a watershed covering 2726 km^2. According to the distribution of salt concentration profile, the estuary was characterized as homogeneous, as the difference of mean salinity concentration between top and bottom layer was less than 15% (Shih et al., 2011).

2.2. Hydraulic and dispersion model

For calculating inundation frequency curve and annual mean salinity of major mangrove wetlands within the Tanshui River system, a quasi-two-dimensional model, the NETSTARS (Network of Stream Tube Model for Alluvial River Simulation) (Lee et al., 1997), was employed. The NETSTARS has been successfully applied to networking rivers in hydrodynamic, sediment transport and salinity simulations (Lee et al., 1997; Hong, 1998; Lin et al., 2005b; Shih et al., 2008, 2011).

The Manning's roughness values and longitudinal dispersion coefficients for the model needed to be tuned to fit the field data in the model validation process. These two parameters of the Tanshui River system have previously been set according to two intensive field measurements in 1994 and bathymetry measured in the same year (Shih et al., 2011). This study used the latest field measurements of water surface elevation and salinity concentration in 2004 (Shih, 2005) and bathymetry measurements in the same year to validate previous parameter set is able to apply in different year. The field measurement on 3 August 2004 had two measurement points illustrated in Fig. 1. Points 1 and 2 used three and two horizontal measure points respectively. At each horizontal measure point data was measured at 0.2 and 0.8 of water depth every 30 min from 7:00 to 20:30. The salinity data were only recorded from point 1.

In order to simulate the tidal behavior and distribution of annual mean salinity, the upstream boundaries were determined by mean annual discharge and the downstream boundary was determined by the tidal data over 8760 h in 2009 (data source: Tenth River Management Office, Water Resources Agency, Taiwan). For the scenario of the year 2100, a sea level rise of 2.42 mm/year was extrapolated and used in NETSTARS for the Tanshui River system simulation. This is in accordance with the tidal gauge records, which have shown sea level rises in the northern Taiwan of 24.2 cm/100 years (Tseng, 2009). The results and further discussions about the future predictions were based on the assumption that the topography and mean annual river flow remain constant in the future. The mean annual discharges were 40.32 cms (cubic meter per second) for the Dahan Creek, 70.52 cms for the Hsindian Creek, and 25.65 cms for the Keelung River.

The inundation frequency curves were computed using NETSTARS simulation results and used to estimate the inundation frequencies tolerance range of the mangrove forests. The following steps were modified from The Nature Conservancy (2009): water level data from the simulated results was ranked from largest to smallest. Each record was assigned a rank value (M) in ascending order, the largest value being assigned a rank value of 1 and the smallest a rank value of n. The inundation frequency (IF) was calculated according to Eq. (1):

$$\mathrm{IF} = 100 \times \left[\frac{M}{n+1}\right] \quad (1)$$

2.3. Field survey of mangrove substrate elevation

The real time kinematic (RTK) technique was applied to measure the mangrove substrate elevation. RTK is a highly precise technique, yielding data with an accuracy of one inch. RTK using GPSs (Global Position Systems) requires two specialized GPS receivers and two radios. Both receivers collect extra data from the GPS satellites that affords better precision (Trimble Navigation Limited, 2006). One GPS receiver was set up as a base station that sent a constant signal to the moving GPS receiver to correct the GPS readings to greater accuracy at the adjacent benchmark from the Tenth River Management Office, Water Resources Agency (WRA),