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Effects of residual hydrocarbons on the reed community after 10 years of oil extraction and the effectiveness of different biological indicators for the long-term risk assessments

Linhai Zhu[a,b], Yongji Wang[a,c], Lianhe Jiang[a], Liming Lai[a], Jinzhi Ding[d,c], Nanxi Liu[a], Junsheng Li[e], Nengwen Xiao[e], Yuanrun Zheng[a,*], Glyn M. Rimmington[f]

[a] Key Laboratory of Plant Resources, Beijing Botanical Garden, West China Subalpine Botanical Garden, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China
[b] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China
[e] Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[f] Global Learning Office, College of Liberal Arts & Sciences, Wichita State University, Wichita, KS 67260-0142, United States

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ABSTRACT

The selection of certain indicators is critical to undertake ecological risk assessments of long-term oil pollution and other environmental changes. The indicators should be easily and routinely monitored, be sensitive to pollution, respond to pollution in a predictable manner, and match the spatial and temporal scales of investigations. To compare the effectiveness of indicators for the long-term risk assessments, this study investigated the multiple ecological effects of chronic oil pollution on the plant community dominated by reed (*Phragmites australis*). The physiology, growth and reproduction of reed, together with the composition and productivity of the reed community, were measured around oil wells that have operated for approximately 10 years in the Yellow River Delta, eastern China. The predictive power of each indicator was evaluated using the coefficients of determination (R^2) of linear regression models established for each indicator and soil Total Petroleum Hydrocarbons (TPH) concentration. The sensitivities of indicators were evaluated by comparing slopes of new established regression lines using standardized data. The top three indicators in terms of predictive power were leaf length, width and number, followed by the Shannon–Wiener index, Pielou evenness index and Simpson's diversity index. Community aboveground biomass, foliar projective coverage and species richness showed predictive power lower than those of the three diversity indexes, but higher than those of leaf net photosynthetic rate, reed height, aboveground biomass and vertical projective coverage of reed plants. Leaf transpiration, chlorophyll concentration and reed stem density showed no significant linear response to elevated soil TPH concentration. In terms of sensitivity, the top three biological indicators were Pielou evenness index, Simpson's diversity index and Shannon–Wiener index, followed by community vertical projective coverage, community aboveground biomass, and species richness. Leaf number, length and width were moderately sensitive, followed by reed coverage, aboveground biomass and height. The sensitivity of net photosynthetic rate was the lowest. The predictive power and sensitivities of indicators were compared in terms of their spatial and temporal scales. In conclusion, scale can be used to facilitate the selection of indicators, and the combination of different indicators may yield improved understanding of the various effects of elevated soil TPH concentration at the different biological levels.

1. Introduction

Increasing oil exploration, manufacture and transportation of petroleum products has resulted in numerous environmental issues (Lin et al., 2002; Peng et al., 2009; Peterson et al., 2003; Ribeiro et al., 2013). Petroleum Hydrocarbons (PH) generally have

* Corresponding author. Tel.: +86 10 62836508.
E-mail addresses: zhengyr@ibcas.ac.cn, zhulh@ibcas.ac.cn, l.h.zhu@163.com (Y. Zheng).

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a direct toxic effect on most organisms (Lin et al., 2002; Peng et al., 2009; Ribeiro et al., 2013), have long persistence in the environment and long-term adverse effects on ecosystems (Culbertson et al., 2008; Li and Boufadel, 2010; Peterson et al., 2003; Reddy et al., 2002). Furthermore, PH may eventually affect human health (Ha et al., 2012; Lu et al., 2012) and associated activities, such as agriculture (Anoliefo and Vwioko, 1995) and tourism (Mendelssohn et al., 2012). Therefore, the ecological risk assessment of oil pollution is of interest to researchers, environmental regulators and legislators. The long-term persistence of PH in the environment highlights the need for further environmental impact studies across a similar or longer period of time.

The development of effective procedures to both assess ecological risk and predict environmental damage from oil pollution depends on the selection of key indicators (Niemeijer and de Groot, 2008). Ideally, key indicators should represent information about the composition, structure and function of the ecological system (Bremner et al., 2006; Dale and Beyeler, 2001), and these indicators should be easily and routinely monitored (Bremner et al., 2006; Dale and Beyeler, 2001; Miller et al., 2006; Niemeijer and de Groot, 2008), be sensitive to oil pollution, respond to oil pollution in a predictable manner and match the spatial and temporal scales of the investigations (Dale and Beyeler, 2001; Niemeijer and de Groot, 2008; Niemi and McDonald, 2004). The predictive power and sensitivity of indicators actually depend on the spatial and temporal scales of variation. Indicators whose scales match that of the investigation will yield higher predictive power and sensitivity, and empirical evidences are needed to support this principle (Wiens, 1989).

A number of studies have investigated the effects of PH on plant individuals, population and the community that contains them (Hester and Mendelssohn, 2000; Meudec et al., 2007; Rosso et al., 2005), based on the premise that plants are the foundation of ecosystem structure and function and are susceptible to environmental perturbations (Miller et al., 2006).

To investigate the PH effects on plants, many studies focus on acute short-term exposure to PH in the laboratory or greenhouse (Lin et al., 2002; Meudec et al., 2007; Rosso et al., 2005; Yu et al., 2012). Under controlled conditions, acute toxicity tests using plant physiological and organismal indicators allow detailed, rapid and cost-effective measures for characterizing the effects of PH on individual plants (Forbes et al., 2006; van Gestel et al., 2001). PH damage the chloroplast, decrease chlorophyll concentration (Rosso et al., 2005; Yu et al., 2012), and inhibit photosynthesis (Chaîneau et al., 2003; Pezeshki et al., 2001; Rosso et al., 2005). Further, PH can reduce plant transpiration when they coat the foliage and block the stomata. Recovery of transpiration begins when the PH dissipate from the leaf surfaces (Pezeshki et al., 2000). Reduced leaf growth due to PH exposure was observed in a variety of plant species (Anoliefo and Vwioko, 1995; Zhang et al., 2007). The Leaf Area Index (LAI) usually declines as the level of PH increase (Zhang et al., 2007). This reduction in LAI is due to decreases in the size and number of leaves (Zhang et al., 2007). PH also can inhibit the height (Lin et al., 2002; Peng et al., 2009; Rosso et al., 2005; Zhang et al., 2007), stem density (Culbertson et al., 2008), biomass and coverage (Culbertson et al., 2008; Lin and Mendelssohn, 2012; Peng et al., 2009; Rosso et al., 2005; Zhang et al., 2007) of plants. These tests allow explorations of the underlying mechanisms for the PH effects under controlled conditions, but they are not practical for the analysis and prediction of plant community behavior in all its complexity in field situations (Forbes et al., 2006; van Gestel et al., 2001; Pezeshki et al., 2000; Zhu et al., 2012).

Community-level indicators are more ecologically relevant to changes in the ecosystem (Attrill and Depledge, 1997). However, few studies have investigated the potential long-term effects of elevated PH levels on plant community in the field (Culbertson et al., 2008; Hester and Mendelssohn, 2000). PH have been found to lower plant community productivity (Kinako, 1981; Mishra et al., 2012; Zhu et al., 2013), simplify their structure (Burk, 1977; Collins et al., 1994; Mendelssohn et al., 1990; Mishra et al., 2012) and reduce their biological diversity (Osuji et al., 2004). This change in community composition depends on the difference in species' sensitivities to PH (Lin and Mendelssohn, 1996; Pezeshki et al., 2000). Usually some species with low tolerance to PH were absent in the following growing season (Burk, 1977; Kinako, 1981). Considering the long-term effects of oil pollution on plant communities (especially the biological diversity), the predictive power and sensitivity of community indicators should be directly compared with indicators at other levels to improve risk assessment (Niemeijer and de Groot, 2008).

To facilitate the selection of indicators and improve the monitoring of effects of elevated PH levels, we investigated long-term impacts of oil pollution on natural community dominated by the reed species (*Phragmites australis*), and compared the predictive power and sensitivity of different indicators from the physiological, organismal, and community levels. We hypothesized that: (1) combining indicators at the different biological levels may improve our understanding of the effects of elevated PH levels; (2) community indicators may carry more predictive power and be more sensitive to elevated PH levels than indicators below the community level.

2. Materials and methods

2.1. Study area and sample design

The Yellow River Delta in eastern China has undergone long-term disturbance due to intensive oil exploitation since 1964 (Bi et al., 2011; Liang et al., 2012), and provided a suitable site for the ecological risk assessment of oil pollution and consequent elevated soil Total Petroleum Hydrocarbon (TPH) levels. This region is a littoral wetland ecosystem that provides a habitat for a number of plant species and is highly valued for both agricultural and tourism development. In this delta, the reed species (*P. australis*) was widely distributed and often dominates the plant community (Chen et al., 2011; Zhu et al., 2014).

The field work was conducted in August 2009 within the Chengdong Oilfield (Shengli Oilfield Company, 118°34′38.35″ E–118°38′08.53″ E, 37°57′34.07″ N–38°01′28.50″ N) in the Yellow River Delta. The study area is adjacent to the National Natural Reserve of the Yellow River Delta, with a straight distance of approximate 32 km to the Yellow River (Fig. 1). The site is sparsely populated and oil extraction continues to be the major production activity (Bureau of Statistics of the Dongying City, 2013). The soil in this area is saline, and its hydrology is affected by rainfall (Yu et al., 2012). The elevation, soil bulk density and water content of the sample plots were listed in Table A.1 of the supplementary data. Reeds dominate these sample plots with several plant species growing under the reeds, such as *Suaeda salsa*, *Scorzonera mongolica*, *Limonium bicolor* and *Aeluropus sinensis* (Table A.2 in the supplementary data).

Based on the information provided by the Hekou Oil Production Plant, Shengli Oilfield Company, SINOPEC, sample plots around each of the five oil wells were established (Fig. 1). The duration of pumping from the oil wells was 7, 8, 10, 12 and 13 years. All wells produced heavy oils.

To obtain a gradient of oil pollution and associated changes of plant parameters, seven distances (0, 5, 10, 20, 30, 50 and 100 m) were determined for each oil well. At each distance, three sampling points were located closely. For each sampling point, a 1 m × 1 m quadrat was established (Silliman and Bertness, 2004). Except for net photosynthetic and transpiration rates of reed leaves, other parameters were measured at three sampling points for each