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Fragmentation effects of oil wells and roads on the Yellow River Delta, North China

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ABSTRACT

Oil exploitation and road development have strongly fragmented the coastal landscapes, leading to profound ecological consequences. The dynamic relationships between oil wells, roads, and landscape fragmentation indices in the Yellow River Delta, China were explored. Oil wells, roads and land cover were mapped from TM images in 1992, 2000, 2006, and 2009, respectively. Changes and relationships were compared among three selected typical sections using linear regression models. We also evaluated the fragmentation effects of oil exploitation on protected wetlands in the Yellow River Delta Natural Reserve (NR). The results showed that oil wells and roads increased greatly. Oil well density and road length density were positively related to patch number and negatively related to patch shape indices. Both drivers have cumulative effects on landscape fragmentation. Influences of old oil wells and roads were stronger than those of new ones. Current management strategies of the NR have failed to effectively prohibit the disturbances of oil activities at the regional scale. The ecological function of protected wetland systems has been damaged by the increase of oil wells. Therefore, based on the principles of landscape ecology, effective approaches were proposed to minimize the negative effects of oil exploitation on the coastal area.

1. Introduction

Coastal landscapes have been strongly fragmented by human activities, resulting in pronounced ecological consequences (Bolger et al., 1997; Franklin et al., 2000; Harrison and Bruna, 1999). The process was closely related to energy production (Copeland et al., 2010; Kiesecker et al., 2009). For instance, commercial exploitation of oil significantly contributed to coastal landscape fragmentation, posing multiple ecological threats to wetlands and coastal ecosystems. One of the most direct effects is vegetation degradation, increasing plant stress and plant death (Nassauer and Benner, 1984). The secondary and indirect effects included hydrology alteration, habitat loss and biodiversity decline (Giao et al., 2008; Ko and Day, 2004; Mitchell, 1978; Neff et al., 2006). The oil-related activities have also contributed significantly to wetland loss (Durell et al., 2006).

At the same time, the exploitation-related road development also affected landscape fragmentation through changing the patterns of land use and human settlement (Forman, 2000; Freitas et al., 2010; Hawbaker et al., 2006; Miller et al., 1996). Previous studies have indicated that road density in oil regions was significantly higher than in non-oil regions and the landscape patterns in oil field regions were significantly fragmented after oil activities (Li et al., 2008; Wang et al., 2005). These mainly focused on landscape changes in oil field regions, however, little attention has been paid to landscape factors, such as oil wells and roads, and their dynamic effects on coastal landscapes even though they were usually recognized as important drivers for landscape fragmentation (Ko and Day, 2004; Li et al., 2008). Understanding the linkages between these exploitation-related factors and landscape fragmentation is necessary to assess the ecological consequences of oil exploitation and plan the future development of oil fields at the regional scale.

The Yellow River Delta is one of the most important regions of petroleum production in China, where the second largest oil field (Shengli Oil Field) in the country is located (Wang et al., 2005). Since the early 1960s, this delta has received increasing disturbances induced by oil exploitation (China Government, 1994; Wang et al., 2002). On the other hand, this delta was a typical ecosystem of littoral wetland, providing key habitats for a variety of wildlife (Tian et al., 1999). The Yellow River Delta Natural Reserve (NR) was established to protect the fragile wetlands and the high species

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diversity, but oil activities still often occurred within and near the NR, threatening the interior character of wetlands (Xu et al., 2004). Therefore, development of oil fields has been a main source of socioeconomic and environmental conflicts here.

There was a body of literature addressing the significant ecological impacts of oil development on the delta at multiple scales (Ji et al., 2007; Li et al., 2009; Nie et al., 2010), yet few studies have directly examined the relationships between oil wells, roads, and the characteristics of landscape fragmentation (Wang et al., 2002). To understand their influences on coastal landscapes, detailed studies are required to analyze the spatial and temporal patterns of those drivers (Ye et al., 2006). Fortunately, remote sense and geographical information system technologies provide effective tools to collect the precise information about oil well distribution, road network and landscape conditions.

Therefore, the objects of this study are to: (1) analyze how oil wells and roads in this delta changed over time; (2) examine the dynamic relationships between oil well density, road length density, and landscape fragmentation; (3) evaluate their potential impacts on protected wetlands in the Yellow River Delta NR.

Table 1
The linear regression models to assess the long-term impacts of oil wells and roads on landscape fragmentation.

Time	Dependent variable	Independent variable
1992–2000	PN, AWMSI, LPI, IJI	O92, R92, O00, R00
2000–2006	PN, AWMSI, LPI, IJI	O92, R92, O00, R00, O06, R06
2006–2009	PN, AWMSI, LPI, IJI	O92, R92, O00, R00, O06, R06, O09, R09

PN: Number of Patches; AWMSI: Area Weighted Mean Shape Index; LPI: Largest Patch Index and IJI: Interspersion and Juxtaposition Index; O: Oil well density; R: Road length density.

2. Study area

The Yellow River Delta is located in the northern part of Shandong Province, China, and on the southwest coast of the Bohai Sea

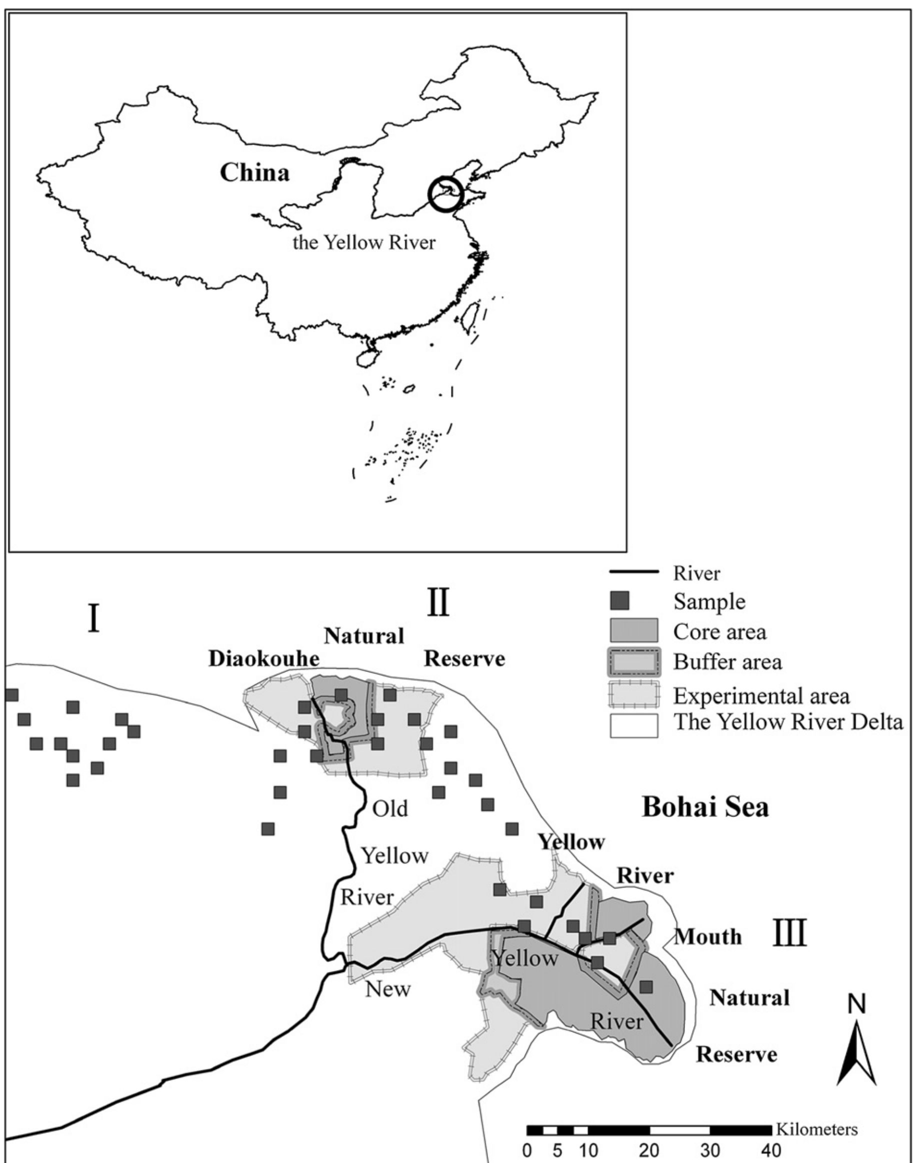

Fig. 1. Study area in the Yellow River Delta, China. Sample units are 2 × 2 km, randomly selected in three sections (I, II, III). The Yellow River Delta NR (grey) included two parts: the Diaokouhe NR and the Yellow River Mouth NR.

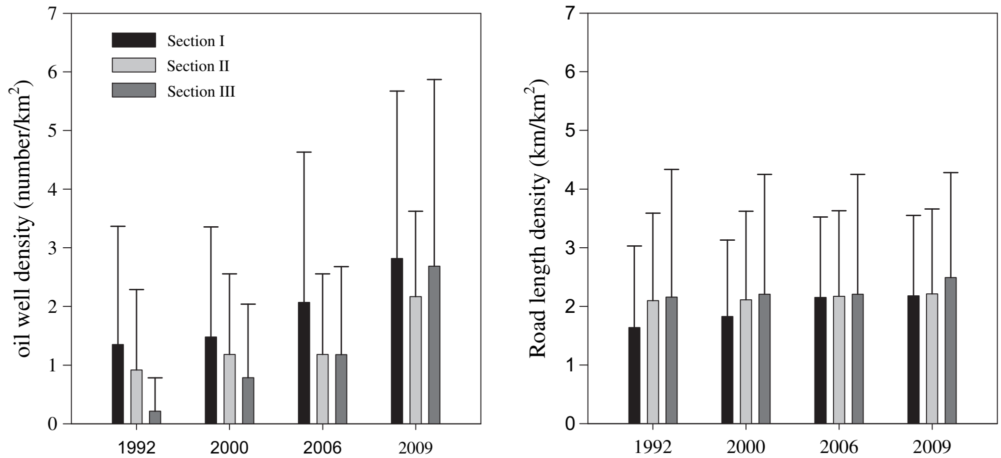

Fig. 2. Means of oil well density (number/km^2) and road length density (km/km^2) in the three sections from 1992 to 2009. Error bars represent standard deviations (S.D.).

(Fig. 1). The massive silt from erosion of the Loess Plateau created the continuous, fast-growing natural delta at the mouth of the Yellow River (Fang et al., 2005; Liu and Drost, 1997). The current course of the Yellow River was formed from artificially changing the old course from Diaokouhe River to Qingshuigou Gully in 1976 (Yue et al., 2003).

The Yellow River Delta NR was established in 1992, with a core area of 58,000 ha, a buffer area of 13,000 ha and an experimental area of 82,000 ha (Fang et al., 2005; Yue et al., 2003). The NR consists of two separate parts: the Diaokouhe NR (north) and the Yellow River Mouth NR (south) (Fig. 1) Here wetland ecosystems provide the birds with habitats for breeding, migrating and wintering, making the region an important stopover in the inland of northeastern Asia and around the western Pacific Ocean for bird migration (Xu et al., 2004). Landscape pattern in the NR is highly heterogeneous due to the salt content in soil. The beach has a higher salt content of soil (more than 3%), in which *Suaeda salsa* Pall. and *Tamarix chinensis* Lour are dominant. The low-lying land along the river has fully moisture content, in which *Phragmitas communis* Trin. is dominant. The higher land has a lower salt content, where *Aeluroupus liitorallis* (Gouan) Parl. Var. *sinensis* Debeanx, *Imperata cylindrical* (L.) Beauv. Var. *major* (Nees) C.B. Hubb. are dominant. The area where salt content of soil is lower than 0.3% has partially became cultivated lands, such as forestland, wheat land and soybean land (Tian et al., 1999).

In addition to Shengli Oil Field, there are several big oil industries within the NR, such as Gudong oil industry, Gudao industry and Zhuangxi industry.

Three typical sections (I, II, and III), located in three sectors of the delta and covering most of the coastal area, were selected, where sections II and III included the wetlands protected by the Diaokouhe NR and the Yellow River Mouth NR, respectively (Fig. 1). In this study area, main human disturbance was oil activity.

3. Methods

3.1. Sample design

Samples were designed to identify the changes of oil wells and roads over time, relate them to landscape fragmentation indices and measure the differences among the three sections. Along a gradient of oil well density, we randomly selected sample grids by the cell length with 2 $\times$ 2 km, covering the main oil field area in the three sections, which could represent the main landscape changes in this region. The total number of samples was 37 (11 in section I, 18 in section II and 8 in section III). The possible spatial autocorrelation of oil well density and road length density were reduced because certain separation distances among samples were maintained in any direction (Hawbaker et al., 2006).

3.2. Data sources

Landsat TM images with 30 m resolution in 1992, 2000, 2006, and 2009 were collected. All images were geo-referenced by a digital elevation model (1:50,000 scale).

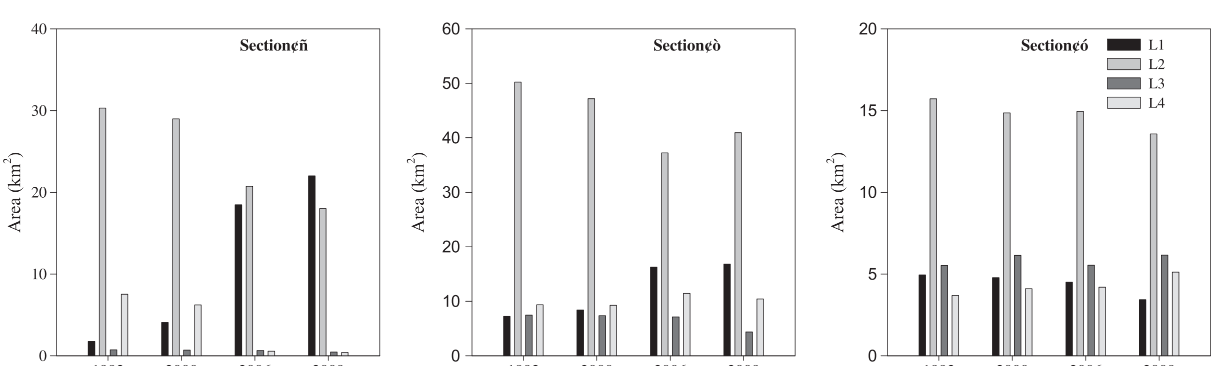

Fig. 3. Changes of land covers (km^2) in three sections from 1992 to 2009. L1: aquaculture area; L2 tidal flat; L3: wetland; L4: farmland.

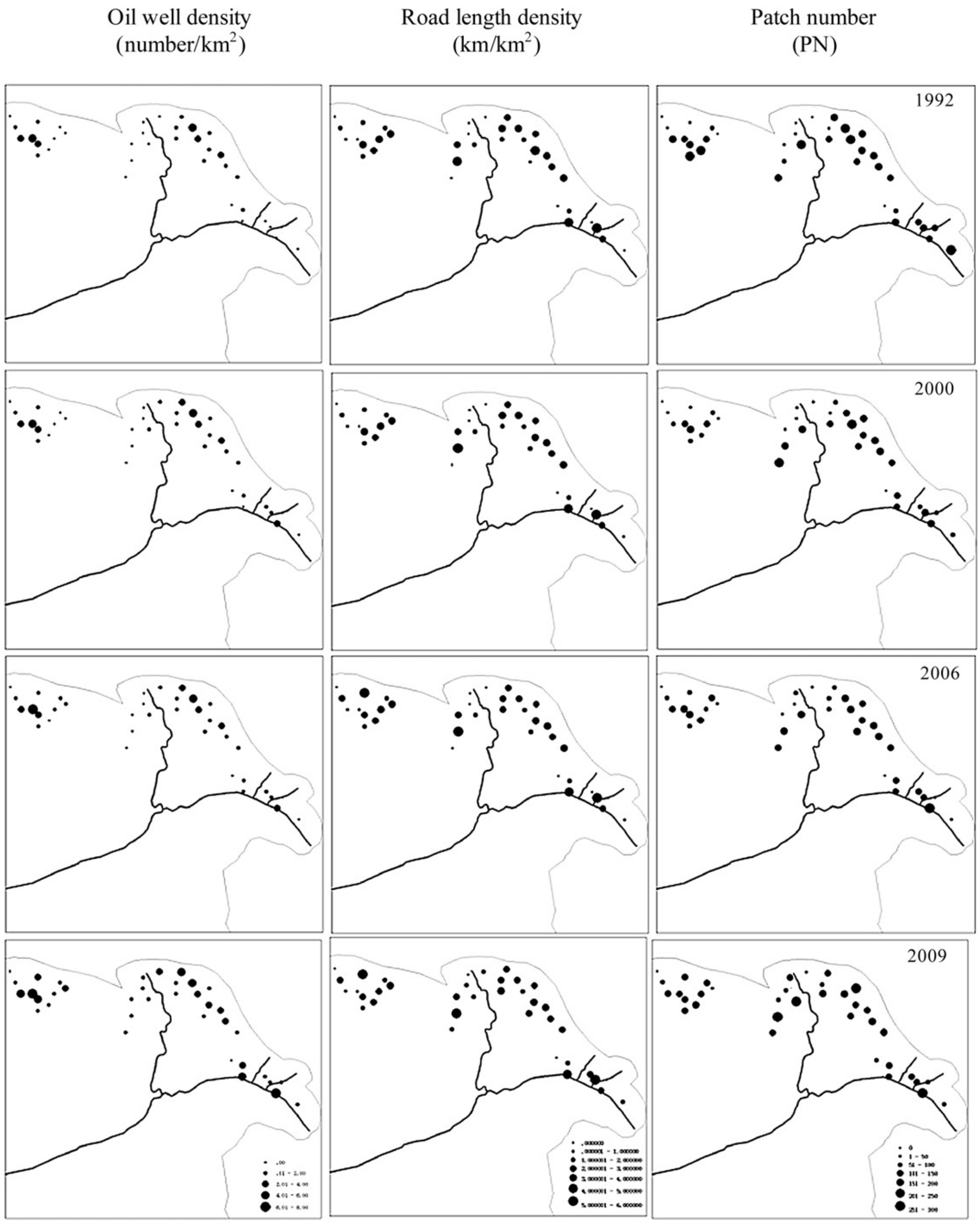

Fig. 4. Distribution of oil well density (number/km^2), road length density (km/km^2) and landscape indices from 1992 to 2009.

There were large amounts of oil wells and quite a few gas wells in the study area, both characterized by white squares with regular distribution (Wang et al., 2002; Li et al., 2008). Because it was difficult to distinguish them by visual interpretation, we mapped them at the same point layer and use the term "oil well" instead of oil well and gas well. Roads, characterized by white or grey lines, were digitized as line layers by visual interpretation. Classification of wells and roads was not carried out due to the lack of informative data.

To identify the land cover, supervised classification method was used in ENVI software. The results of visual interpretation and land cover classification were checked in field in 2009 with an accuracy of more than 90% and 80%, respectively. Oil well density (number/km^2), road length density (km/km^2) and areas of land cover (km^2) in each sample were calculated for by ArcMap 9.2.

Fragmented characteristics of land cover were measured by FRAGSTATS 2.0 (McGarigal and Marks, 1995), using the following landscape indices: Number of Patches (PN), Area Weighted Mean Shape Index (AWMSI), Largest Patch Index (LPI), and Interspersion and Juxtaposition Index (IJI). These indices were selected for their ability to describe the variations in landscape pattern with the ecological significance (Neel et al., 2004; Riitters et al., 1995; Wu, 2004).

To describe the dynamic influences, changes of oil well density, road length density and landscape indices were evaluated for three time spans (1992–2000, 2000–2006, and 2006–2009).

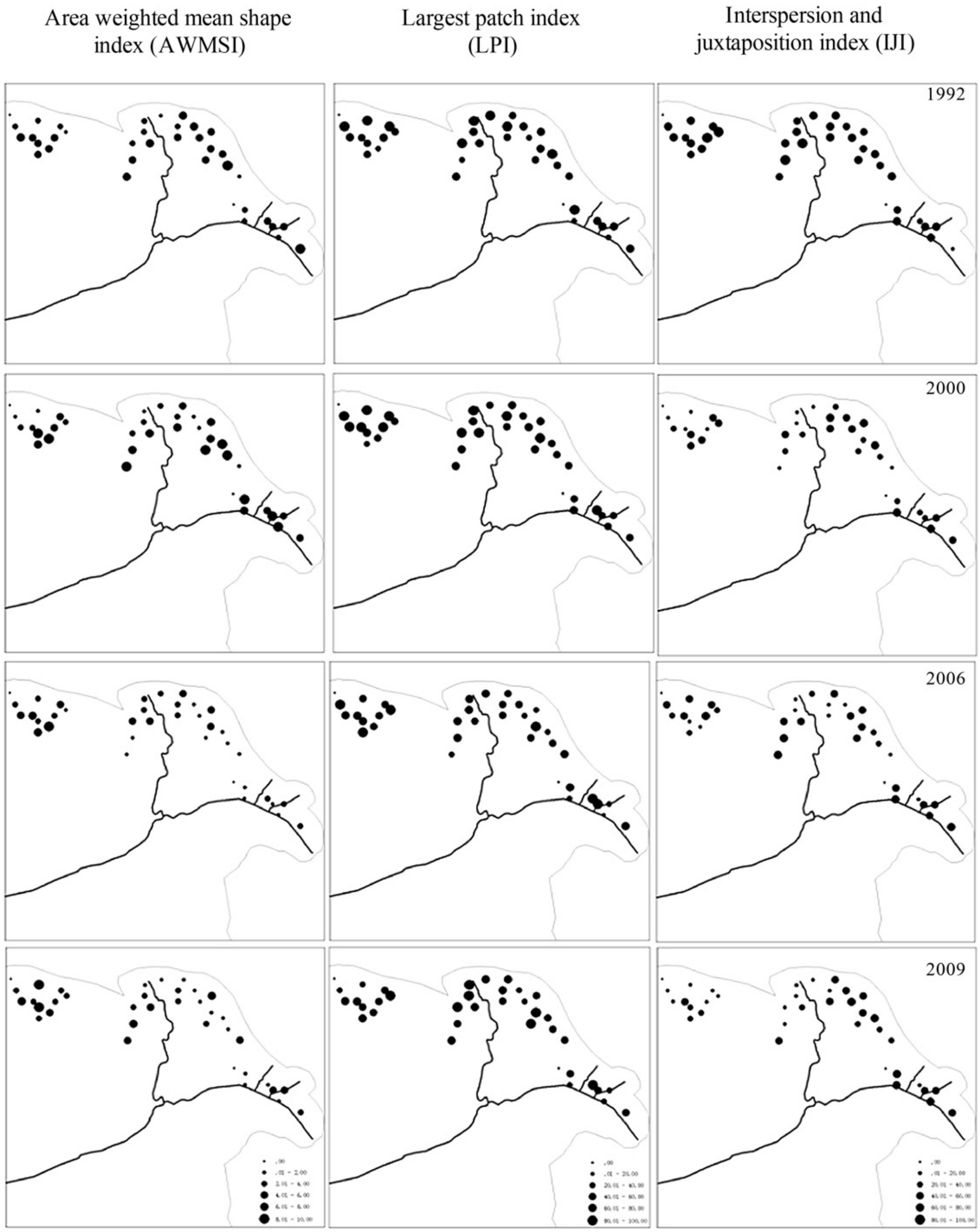

Fig. 4. (*continued*).

3.3. Linear regression models

Firstly, oil well density and road length density were transformed to normal distribution to meet the assumptions of regression analysis (Zar, 1996). Then, we used linear regression models to explore the dynamics relationships between the densities and landscape indices.

To evaluate the long-term effects, we measured the independent variables from the initial period. For example, for the period 1992–2000, the independent variables included oil well density and road length density in 1992 and 2000, respectively. Similarly, for the period 2000–2006, they included oil well density and road length density in 1992, 2000, 2006, respectively (Table 1). All variables with more than 60% correlation were deleted in the regression models. The variables with individual *P*-values >0.05 were excluded by a backward elimination procedure during the regression analysis. Compared with forward and stepwise selection schemes, backward elimination has significant advantages (Mantel, 1970). Finally, we examined the regression coefficients (R^2) and standard errors (SE) to evaluate the regression models. All analyses were done by SPSS 13.0.

3.4. Spatial distribution of oil wells in the NR

In order to highlight the influences of oil wells on the protected wetlands, we mapped spatial distribution of oil wells in the NR.

Table 2
Linear regression models ($P < 0.05$) relating PN to independent variables (oil well density and road length density in 1992, 2000, 2006 and 2009, respectively), after backwards elimination.

Time period	Section	O92	R92	O00	R00	O06	R06	O09	R09	SE	R^2
1992–2000	I		+							23.45	0.63
	II	+		+						36.79	0.22
	III		+							47.02	0.73
2000–2006	I				+					21.23	0.84
	II	+								45.51	0.23
	III	+								34.23	0.65
2006–2009	I				+	+				27.01	0.35
	II	+		+						63.45	0.34
	III			+						7.92	0.87

O: oil well density; R: road length density; SE: standard err of the estimate; R^2: R square.
+: Significantly positive relationship.

Many ecologists have applied buffer analysis to identify the pattern of drivers in protected areas (Radeloff et al., 2010), but it was difficult to estimate the influences of oil wells on the interspaces by buffer analysis since the Yellow River Delta NR was divided into two separate parts. In this study, therefore, we used grids with cell length 2×2 km to describe the distribution of oil wells. The cell length represented a conservative distance influenced by one oil well on local environments (Daan and Mulder, 1996).

4. Results

4.1. Growth of oil well density and road length density in three sections

Oil well density and road length density in the three sections have increased from 1992 to 2009 and the growth rates of oil well density were significantly higher than road length density (Fig. 2).

Among the three sections, section III exhibited the highest growth rates of mean and standard deviation (S.D.) of oil well density, which increased from 0.22 and 0.56 in 1992 to 2.69 and 3.13 in 2009 (1122% and 458% growth). However, the absolute values of both variables in section I were high, with the values of 1.35 and 2.01 in 1992, 2.82 and 2.72 in 2009 (108% and 35% growth). The high values of S.D. in sections I and III indicated highly heterogeneous patterns of oil well density in 2009. Compared with the S.D. of oil well density in 2009, these of road length density were lower in the three sections (e.g. 1.37, 1.45 and 1.79, respectively), indicating relatively homogeneous patterns of road length density.

4.2. Changes of land cover in three sections

We mapped four land cover classes: aquaculture area, tidal flats, wetland and farmland according to a published vegetation map of this NR[1] (Fig. 3). Land cover in sections I and II have changed greatly. For example, the two sections exhibited high growth rates of aquaculture area (1150% and 132%). However, land cover in section III was stable, exhibiting moderate growth rate of wetland (12%) and reduction rate of aquaculture area (30%).

4.3. The relationships between oil well density, road length density and landscape fragmentation indices

Fig. 4 showed substantial pattern changes of oil well density, road length density and landscape indices over time. Oil well density and road length density were positively related to PN and negatively related to AWMSI, LPI and IJI, respectively. Due to the significance between PN, AWMSI and oil well density, road length density, their dynamic relationships were further analyzed using linear regression models.

The regression results showed that past oil well density and road length density were significantly related to current landscape fragmentation. For example, between 2006 and 2009, 2000 road length density and 2000 oil well density were significantly related to PN of section I, 1992 oil well density and 2000 oil well density were significantly related to that of section II, and 2000 oil well density was significantly related to that of section III (Table 2). At the moment, 2006 road length density, 2000 road length density and 2000 oil well density were significantly related to AWMSI of the three sections, respectively (Table 3). Oil well density was the main factor affecting patch number, whereas road length density was the main one affecting patch shape.

4.4. The influences of oil wells on the Yellow River Delta NR

The NR has exhibited obvious growth of oil well density from 1992 to 2009, with the average value ranging from 0.11 in 1992 to 0.45 in 2009. The pattern of oil wells has also changed greatly, which mainly sprawled from the unprotected areas to the protected areas in the NR. In the Diaokouhe NR, almost all of the protected areas have suffered the disturbances of oil wells since 2000. In the Yellow River Mouth NR, however, oil wells were mainly observed in the experimental area in 1992 and were also found in the core area in 2009 (Fig. 5).

5. Discussion

Recently, many studies have focused on the ecological effects of oil activities on coastal landscapes. The combination of these disturbance factors has changed land cover pattern and increased landscape fragmentation in oil fields (Ko and Day, 2004; Li et al., 2008; Wang et al., 2005). In this study, we highlighted the dynamic relationships between oil wells, roads and landscape fragmentation in the Yellow River Delta by random sample designation and spatial analysis of GIS. The management of coastal environments calls for interdisciplinary study and innovative methodologies that consider processes occurring at multiple spatial scales. An understanding of these relationships at landscape scale, therefore, is very helpful for successful management of coastal systems in oil filed.

With the development of oil fields, this delta has experienced a high rate of landscape fragmentation which was largely contributed to the increase of oil wells and roads (Figs. 2 and 3). However, road growth was more moderate than oil well growth, because road was a relatively permanent element of landscape (Freitas et al.,

[1] http://www.yrdsd.com/zrbhq/0401.htm.

Table 3
Linear regression models ($P < 0.05$) relating AWMSI to independent variables (oil well density and road length density in 1992, 2000, 2006 and 2009, respectively), after backwards elimination.

Time period	Section	O92	R92	O00	R00	O06	R06	O09	R09	SE	R^2
1992–2000	I				–					2.48	0.29
	II				–					1.56	0.47
	III				–					1.06	0.94
2000–2006	I				–					1.26	0.88
	II				–					2.11	0.26
	III			–						1.04	0.98
2006–2009	I						–			2.42	0.68
	II				–					2.91	0.73
	III			–						1.02	0.99

O: oil well density; R: road length density; SE: standard err of the estimate; R^2: R square.
–: Significantly negative relationship.

2010), determined not only by exploitation intensity but also by land cover (Miller et al., 1996; Hawbaker et al., 2006). For instance, in section I, the dominant tidal flat has largely been changed into aquaculture area, which required expansion of roads to meet access needs, but the lower road growth in sections II and III was related to the wetlands protected by the NR, which constrained the road development (Hawbaker et al., 2006). Therefore, the ecological effects of roads should be evaluated and the pattern of road network should be planned before oil exploitation.

The fragmentation effects of oil wells and roads in this delta mainly included an increase of patch number and a simplification of patch shape. The landscape consequences depended on the spatial patterns of oil wells and roads and were observed after a time-lag. Understanding the cumulative effects is very essential to assess and predict the ecological risk of oil exploitation. In the early period (1992–2000), past road length density was the main factor affecting landscape changes in three sections. However, in the later period (2006–2009) when road networks in oil field have been completed, past oil well density was strongly related to fragmentation indices, especially in sections II and III, becoming an important predictor of fragmentation. Although the vegetation disturbed by oil activities could self-restore to a certain degree after

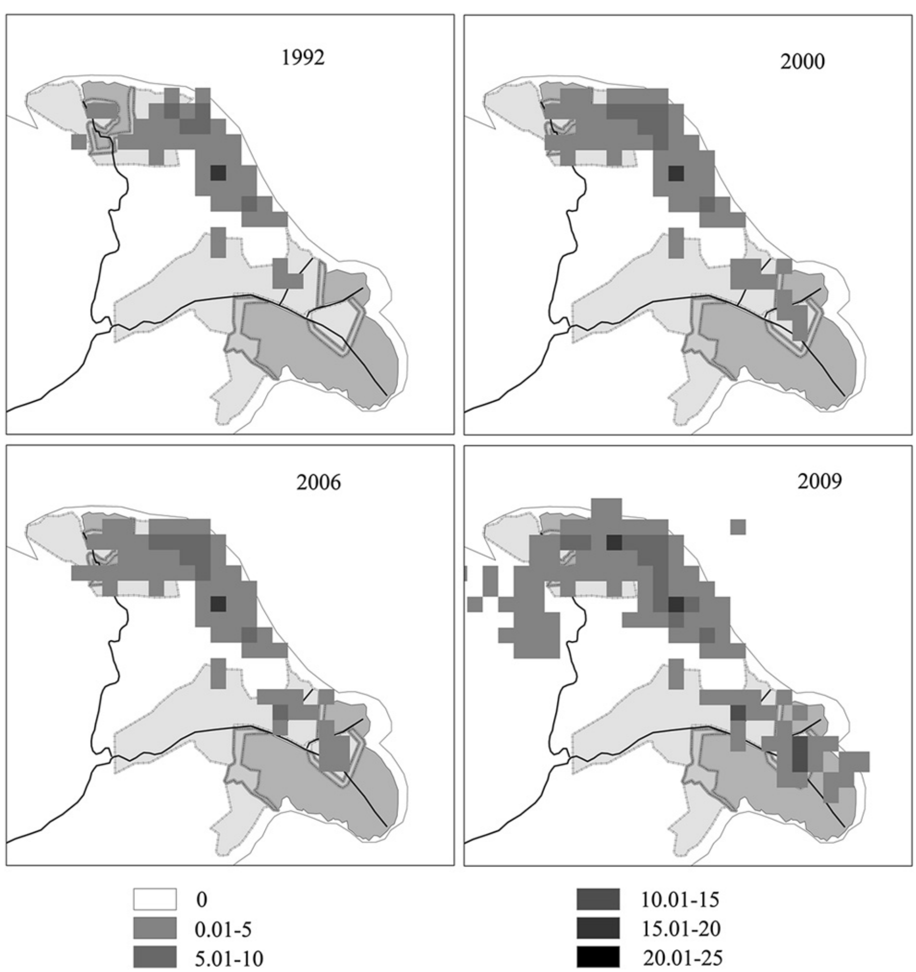

Fig. 5. Distribution of oil well density (km/km^2) in the Yellow River Delta NR from 1992 to 2009. Northern Part: the Diaokouhe NR; Southern part: the Yellow River Mouth NR.

10 or more years (Wang et al., 2002), the fragmentation effects of oil wells and roads still existed, affecting some key ecological processes in coastal ecosystems (Beier and Noss, 1998). In this delta, however, old oil wells and roads were awfully neglected in the process of ecological restoration because ecological damages at the initial stage of oil well and road construction were more easily observed than at the later stage. Therefore, effective conservation and restoration strategies after oil exploitation should not only consider the quantity of oil wells and roads, but also consider the ages of them, and especially the distribution patterns of old ones.

Although our study has demonstrated the landscape influences of oil wells and roads, the spatial results largely depended on the available data. We carefully mapped the individual wells in the tidal flat and aquaculture area, but some wells in farmland and constructed land were unable to be identified due to the low resolution of TM images. Consequently, we might underestimate the oil well density because the unidentifiable ones were excluded during the visual interpretation. In addition, only roads with the width more than 8 m in the region could be detected by TM images (Wang, 2008), therefore, the estimation of road length density was also conservative. Despite of the limitation of data sources, the results of GIS analysis were still meaningful and helpful. It suggested that the density of oil well and road are good indicators of the threats to coastal landscapes because the influences of urbanization and agriculture on this region were more moderated compared with other territorial regions. In addition to landscape fragmentation, they could also indicate vegetation degradation, soil pollution and species diversity decline (Tian et al., 1999; Wang, 2008; Wang et al., 2002).

The natural reserve is established to counteract the degradation of coastal ecosystems and maintain the high biodiversity. However, in many cases, current management strategies of natural reserves in coastal areas have failed to achieve their conservation objective at large scale (Rioja-Nieto and Sheppard, 2008). The Yellow River Delta NR has played an important role in limiting the disturbances of oil exploitation, leading to an increase of wetland area (Section III) and partly preventing landscape fragmentation (Fig. 4), but it failed to strictly prevent the activities within the administrative boundaries. In the NR, the main disturbance factor became oil wells. Oil wells sprawled from experimental areas to core areas of the NR, resulting in direct ecological impacts, such as vegetation damage and soil disturbance (Wang et al., 2002). The spatial analysis also showed that the influence of oil wells on the Diaokouhe NR was stronger than on the Yellow River Mouth NR (Fig. 5). Unfortunately, wetlands in this part have received less attention even though oil activities have already occurred in core areas, because main conservation efforts were focused on the Yellow River Mouth NR due to its larger area.[2] Therefore, to achieve the conservation objectives, the size of protected areas must be adequate and the management strategies of protected areas must be made at a regional scale.

In addition, the effectiveness of NRs not only depends on their ability to stop landscape fragmentation within their boundaries, but also depends on their connections to other wild areas and semi-wild areas in their surroundings (Beier and Noss, 1998). Increased landscape fragmentation leads to impairment of patch connectivity. The interspaces of the Diaokouhe NR and the Yellow River Mouth NR have exhibited heavy increase of oil wells (Fig. 5). Consequently, the protected areas in the two separated NRs were isolated by the disturbances, increasing the barrier effects on the wetland and posing potential threats to the biodiversity in this region. For instance, oil well-driven landscape fragmentation has limited the habitat availability for area sensitive species, the red-crown crane (*Grus japonensis*), one of the state-listed endangered birds in this delta (Cao and Liu, 2007). Wetland habitat fragmentation or loss has increased the distances between desirable habitat (resource) patches and lead to impairment of patch connectivity, constraining the movements of individuals and hampering the conservation of this population (Pascual-Hortal and Saura, 2006; Yue et al., 2003). Therefore, stronger efforts focusing on oil well development within and near protected areas are needed. According to our study, proposals for conserving the key specie in coastal areas are to: (1) identify resource patches and assess their current conditions, (2) protect those resource patches from direct disturbance of oil wells and roads, and (3) maintain the natural patch connectivity and ecotope diversity in the whole coastal area.

Many coastal areas are currently under stress caused by oil activities. Key coastal system has a special significance for the health of both marine and territorial environments. To aid the goals of long-term conservation and maintenances of those ecosystems, it is more important to facilitate the natural processes than only to protect the current landscape patterns (Hinchey et al., 2008). From the point of view of landscape ecology, providing ecological engineering approaches to decrease habitat fragmentation, protecting important natural corridors from the growth of oil well and road, preventing oil exploitation activities within and near the boundaries of NR, designing enough protected areas, and blending landscape-level planning with biodiversity offsets are effective measures which would minimize the negative effects of oil exploitation on the Yellow River Delta.

6. Conclusions

Oil production in the Yellow River Delta has increased dramatically since the 1970s. These oil exploitation-related activities have affected coastal landscapes, resulting in significantly fragmentation. The direct landscape drivers are oil wells and roads, which increased greatly in this delta.

We analyzed the relationships between densities of oil wells, roads and landscape fragmentation. Our results demonstrated that oil wells and roads have played substantial roles in fragmenting the coastal landscapes in the delta. The influences mainly included an increase of patch number and a simplification of patch shape. Oil well density mainly affected patch number, while road length density mainly affected patch shape.

In addition to the direct fragmentation effects, the potential consequences of fragmentation were also great on this delta. For instance, oil wells and roads have cumulative effects on landscape fragmentation. Old roads mainly affected landscape changes in the early period, while old oil wells mainly affected landscape fragmentation in the later period. We should pay more attention to old oil wells and roads during the process of ecological restoration. Conservation and restoration strategies would consider the ages of oil wells and roads, the distribution pattern of old ones.

Oil-related activities have also contributed significantly to wetland loss, leading to the barrier effect on the key habitats in the NR. Especially, the Diaokouhe NR suffered more impacts than the Yellow River Mouth NR. Therefore, strategies of management and conservation must be considered at regional scale. More attention should be paid to the unprotected wetlands in the interspaces between the two individual NR. Planning strategies must be able to increase the landscape connectivity for key ecological processes.

In brief, based on the principles of landscape ecology, understanding of temporal and spatial patterns of landscape drivers and their landscape effects could provide new insight into the planning and management of coastal areas in oil field.

[2] http://news.sciencent.cn/htmlnews/2010/5/232234.shtm.

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