



# Dynamic wetland mosaic environments and Asian openbill habitat creation in peri-urban Bangkok

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Published online: 1 December 2017

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## Abstract

This study examined the spatial relationships between various types of wetland and the distribution of Asian openbills (*Anastomus oscitans*) as an indicator species in a peri-urban industrial area of Bangkok. We (1) mapped the study area by using a time series of aerial photographs combined with field validations, (2) conducted a 2-year line census of Asian openbills in the field, (3) interviewed local farmers and residents about Asian openbill populations and spatial distributions, and (4) conducted an overlay analysis to statistically identify land-use factors related to spatiotemporal changes in the Asian openbill population and distribution. We found that the number of ponds increased from 1980 to 1999 and then decreased from 1999 to 2010, but the remaining ponds were relatively temporally stable in their numbers and volumes. Paddy fields were primarily replaced by aquaculture ponds, and excavated soil was used as fill in adjoining built-up areas. The number of coconut, banana, mango and other trees planted around the ponds increased during the period, providing Asian openbill habitat. The openbills fed in the remaining paddy fields, and the simultaneous existence of various rice cultivation stages in the area provided a stable year-round source of food. Overall, the results indicated that this expanding urban–rural mosaic landscape could include further spatial distribution of Asian openbills in the future. This study of Asian openbills reveals just one example of the ecosystem services provided by developments creating pond–fill landscapes, and the methods used may be applicable in other similar continental delta regions.

**Keywords** Delta · Wetland · Urbanization · Ecosystem services · Asian openbill · Bangkok

## Introduction

Many large cities are located mainly on delta lowlands and face serious environmental challenges in the face of global warming and sea level rise (Giosan et al. 2014). Large Asian cities on deltas under a monsoonal climate represent both typical and remarkable examples of these challenges (Yeung 2001). Although the environmental issues raised by climate change have received a great deal of attention by many international organizations worldwide (e.g., World Bank 2010),

less attention has been paid to local and indigenous environmental conditions in various deltas. In particular, the agricultural land development processes prior to urbanization that could be adapted to natural delta ecosystems to maximize deltaic ecosystem services have not been well considered in the context of current global environmental issues (Seto 2011). These pre-urbanization environmental conditions could have an influence on current urbanization processes and patterns, especially the formation of the urban fringe’s urban–rural mosaic landscape through landform transformation methods (Hara et al. 2005). Such fringe areas have many industrial parks and other types of emerging land uses that produce global-scale environmental impacts (McGee 2008); hence, it is quite important to mitigate these environmental loads in effective ways, for example, by maximizing ecosystem services in urban–rural mosaic landscapes (Hara et al. 2010). However, it is still difficult to evaluate these mosaic landscape ecosystem services, because the landscapes are very complex and often chaotic, include many landscape patches and material flows, and show the properties of an open and complex system (Portugali et al. 2012).

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There may be some constraints controlling the overall landscape in these delta regions, which consist of many complex landscape patches. Hara et al. (2008) reported that soil availability was a major constraint in many monsoonal Asian continental deltas, such as that on which Bangkok is built. These deltas were first mainly used for floating rice cultivation because of the favorable hydro-geographical and climatic conditions (Takaya 1987). Later, irrigation canal systems were developed and annual rice paddy irrigation became possible after the installation of so-called modern agricultural engineering, especially by Dutch engineers (ten Brummelhuis 2006), who were very influential in the development of civil engineering in monsoonal Asia (Hara et al. 2014). The agricultural landscape now includes networks of newly developed civil engineering arterial canals along with indigenous autonomous irrigation ditches and includes privately held large-scale agricultural land parcels as part of the overall landscape matrix (Davivongs et al. 2012).

In many areas, these landscapes were then urbanized and agriculture was diversified following landform transformation or pond–fill combination development (Hara et al. 2005). In continental deltas, fill material for housing foundations is often obtained by excavation on adjoining land parcels, creating an uneven land surface pattern consisting of various ponds and filled areas. The remaining rice fields can utilize a wide variety of rice growing methods, including direct-sowing and transplanting, that vary according to labor cost and availability, which is in turn often influenced by the level of urbanization. Also, rice fields can be transformed into other uses such as orchards and vegetable fields by using small-scale surface transformations such as raised bed systems (Molle et al. 1999). These land-use diversifications combined with temporal dynamics in water level and varying plot-level land management practices can create dynamic landscape mosaics that include both dry and wet landscape units, thereby providing dynamic ecosystem services for humans and other species, particularly with respect to waterbirds and their feeding, nesting, breeding, and other activities (Round 2008).

These unique landscapes have been evaluated mostly from the viewpoint of human living spaces, such as landscape and land-use planning (Hara et al. 2010), urban and agricultural economics (Vagneron 2006), local food systems (Tsuchiya et al. 2015), and urban water environments (Honda et al. 2010). The biodiversity of these landscapes has been less studied (e.g., Amano et al. 2008; Bellio et al. 2009; Sundar and Kittur 2013), possibly because these urban-agricultural landscapes are considered to be of less value as they are both short-lived and gradually disappearing. Hence, whereas many ecologists have studied conservation of waterbirds and other wildlife species in large-scale natural wetlands, including mangrove areas and tidal flats in this area (e.g., Duckworth et al. 2002; Round 2006; Mohd-Azlan and Lawes 2011; Chaiyarat and Eiam-Ampai 2014), researchers may put much

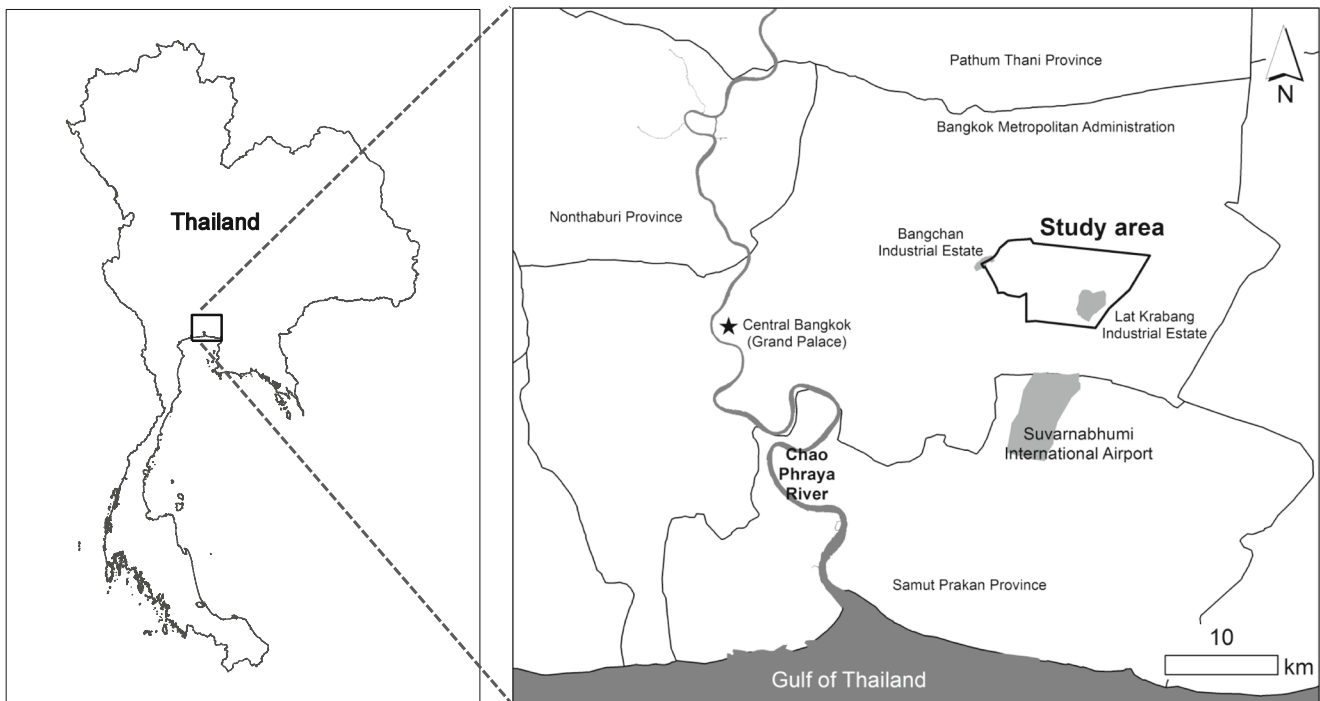
less value on studies of biodiversity in urban-agricultural landscape areas. However, Hara et al. (2008) reported that these urban–rural mosaic wet landscapes have been long-lasting, some for more than 30 years. Also, urbanization is still proceeding in many areas along with population increases in fringe areas (Murakami et al. 2005), inducing a continuous dynamic of new urban–rural mixed landscapes. Moreover, from a long-term point of view, it is possible that increased urbanization will stop at some point and urban areas may actually begin to shrink, which has occurred in some developed countries (Haase et al. 2014). Of course, projecting the future of these landscape mosaics is not easy and is subject to each area’s particular land and socioeconomic conditions; however, these mosaics can be long-lasting and should not be neglected.

In this case study in Bangkok, we addressed the research question: how important are the ecosystem services of urbanization-induced deltaic dynamic wet landscape mosaics to sustaining biodiversity? For this purpose, we identified almost a half century of landscape changes in an urban fringe area, including agricultural, residential, and industrial land uses, with a special focus on detailed wetland landscape units. We then focused on the Asian openbill (*Anastomus oscitans*) as an indicator species of these wet landscapes, and conducted an interval line census survey in relation to landscape patterns. We also interviewed local residents on the issues of landscape changes, water management methods, and changes in the rough number of Asian openbills that have been affected by landscape changes. We conducted a spatial analysis using GIS to ascertain statistical relationships between landscape changes and Asian openbill distribution. We discussed the spatio-temporal importance of human-induced unplanned wetland mosaics and their potential as a dynamic long-lasting habitat for species such as waterbirds in a complex system.

## Methods

### Study area

The study area is located north of the Bangkok Suvarnabhumi International Airport (completed in 2006) and includes Lat Krabang Industrial Estate (established in 1978) in the south-eastern part and Bangchan Industrial Estate (established in 1982) in the northwestern part (Fig. 1). The annual precipitation is 1482 mm, which is concentrated in the rainy season (70%; June–October, average temperature is approximately 28.5 °C), as compared to the dry season (November–February, average temperature is approximately 28.7 °C) and the hot season (March–May, average temperature is approximately 30.8 °C) (BMA et al. 2009). The study area covers 3 administrative districts, MinBuri, Lat Krabang, and NongChok, in the eastern fringe of the Bangkok Metropolitan



**Fig. 1** Study area

Administration (BMA), having a population of approximately 460,000 in 2013 (BMA 2015). Particularly after completion of the Suvarnabhumi International Airport in 2006, urbanization has been proceeding quickly in this area. In fact, in 2005, these 3 districts had a population of approximately 380,000 (BMA 2015), indicating a relatively brief period of fast urbanization. Geomorphologically, the study area is situated in the lowest part of the continental Chao Phraya Delta, and has an extremely flat landform. Hence, it inherently has pre-existing wet environments, and after agricultural development, it generally consists of irrigation canal networks, rice fields and other agricultural fields; various ponds and reservoirs; and other related features (Takaya 1987). Urbanization has been encroaching into these wet agricultural landscapes. This urbanization has consisted of the expansion of urban land uses, especially housing and commercial and industrial lands that required the use of fill, meaning that many ponds were created during fill excavation. As a result, a complex and dynamic wet landscape mosaic has emerged.

### Indicator species

We focused on the Asian openbill as an indicator species of wet landscape mosaics. Its average height is 80 cm, and it is distributed from India to Vietnam (Round 2008). In the past, it migrated into areas of Thailand during the dry season for nesting; however, currently it has become a resident bird. Its world population is estimated at 300,000, of which about 226,200 were located in 25 major colonies in Thailand in

2004 (Round 2008). It can adapt to relatively dry conditions, and therefore is not as dependent on large-scale natural wetlands as other species of storks. It feeds on frogs, insects, crabs, and snails (Kahl 1971), especially the channeled applesnail (*Pomacea canaliculata*) in rice fields, wetlands, and canals. It flies long distances and uses isolated trees, including dead trees and utility poles, when searching for food or to rest. In Thailand, it nests from November to May (i.e., not during the rainy season). It uses trees and bamboo along canals and rice fields for nesting. According to Round (2008), there was large colony in the area north of Bangkok until the early 1980s. As a result of human activities, such as tree cutting, road building, and transforming land use from rice fields to fishponds, this large colony split into several smaller colonies inhabiting a larger area. In 1997, 6396 nests were observed in Lat Krabang District, which is largely included in our study area. This species can adapt to some elements of manmade landscapes (Datta and Pal 1993), so that it is suitable for use in our study area as an indicator to evaluate various aspects of wet urban–rural landscape mosaics.

### Digital map preparation

In preparing the digital maps, we first obtained black-and-white aerial photographs covering our study area for 1967 at a scale of 1:50,000, 1980 at 1:30,000, 1987 at 1:20,000, and 1999 at 1:50,000 from the Royal Thai Survey Department. These photos were scanned at 1200 dpi, and geo-referenced at WGS1984-UTM47N. In addition, we also used 2010 Bing

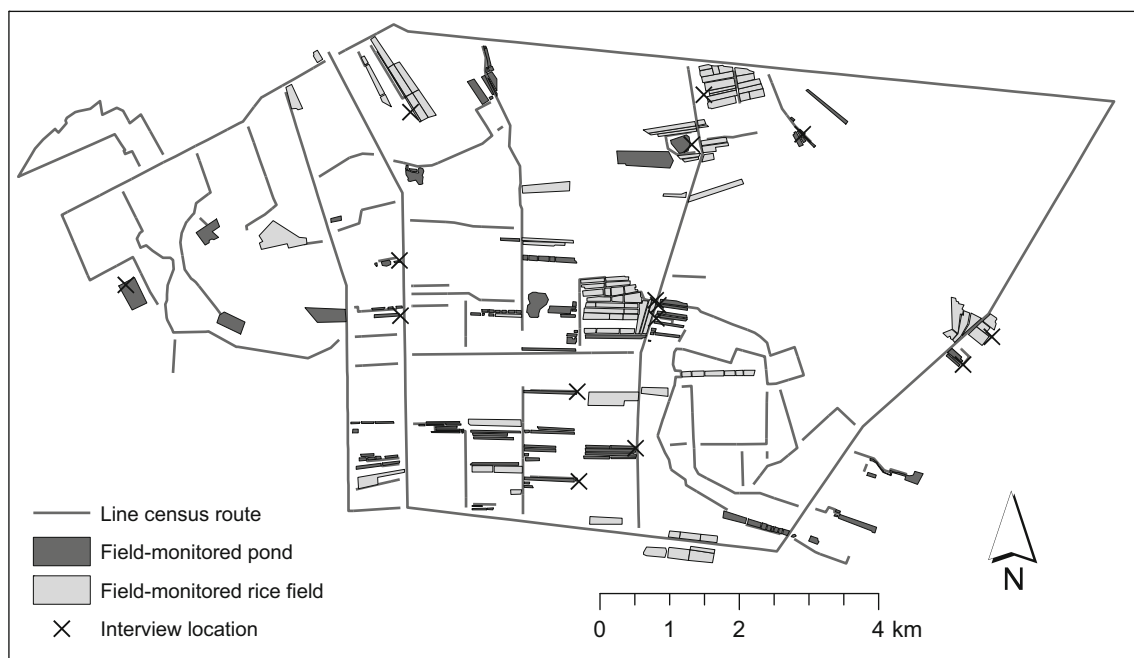
Maps Aerial imagery to support the geo-referencing to produce land-use data for 2010. We then produced our original digital wet landscape dataset using ESRI ArcGIS version 10.0. First, we derived ponds in a vector polygon format from the geo-referenced aerial photos and the Bing Maps Aerial imagery through visual interpretations. We also extracted trees near the ponds. The trees were identified by their crowns by visual interpretation and extracted as vector line data, meaning that continuous crowns were not separated based on their trunks. In this way, we calculated the area of each pond and the proportion of tree line length to the pond's perimeter (based on ArcGIS Jenks' natural breaks in the 2010 map, the final categories were: no trees, 0%; few trees, 0.1–29.2%; medium amount of trees, 29.3–61.8%; and many trees, 61.9–100%) and their transitions through time. The uses of some of these ponds were verified during our line census field survey discussed later. This detailed extraction process allowed for statistical investigations of the ponds and the Asian openbills that can use the trees and ponds for important feeding and nesting habitats.

We then constructed other land-use maps for these 5 periods. We used a 2003 vector land-use dataset at a scale of 1:4000 from the BMA as a source map. Because the dataset was somewhat old and appeared to include several errors, we first modified and improved this map using recent Google Earth images and field validation during our field survey (discussed below). Then we constructed land-use maps for the 4 past periods by modifying the most recent land-use data. However, because it was difficult to distinguish detailed agricultural and urban land uses from the black-and-white aerial

photos, we integrated land uses into 4 major categories: urban, canal, pond, and farmland (mostly rice fields).

### Interval field line census for Asian openbills and land uses

We conducted a count of Asian openbills and investigated rice fields and pond use along the lines shown in Fig. 2. This census was based on basic bird monitoring procedures used in previous research (e.g., Sundar 2004; Buij and Croes 2013), and was conducted on 7–13 March, 20–23 July, and 23–28 November 2013, and on 17–20 March, 14–15 June, 24 August–2 September, and 20–23 December 2014. The survey was conducted on each day between 09:00 and 16:00 to focus on Asian openbills' daytime behaviors and for convenience. The census line routes were selected to cover the study area equally, and consisted of roads, agricultural pathways, and concrete pedestrian and bike pathways along the canals. During the line census, we used a vehicle or bicycle, or walked in the case of small pathways. We immediately stopped when we spotted Asian openbills. Because this area is quite flat, we had good visibility (as much as 900 m from the line in the field); hence, our lines allowed us to cover almost the entire area. We used a Canon EOS6D GPS digital camera with a 400-mm telephoto lens to photograph the openbills, and we used Nikon Aculon T11 field glasses to observe them. We recorded the number of Asian openbills at each observation point as well as their behaviors (catching food, resting, moving, roosting, and breeding). We also photographed the



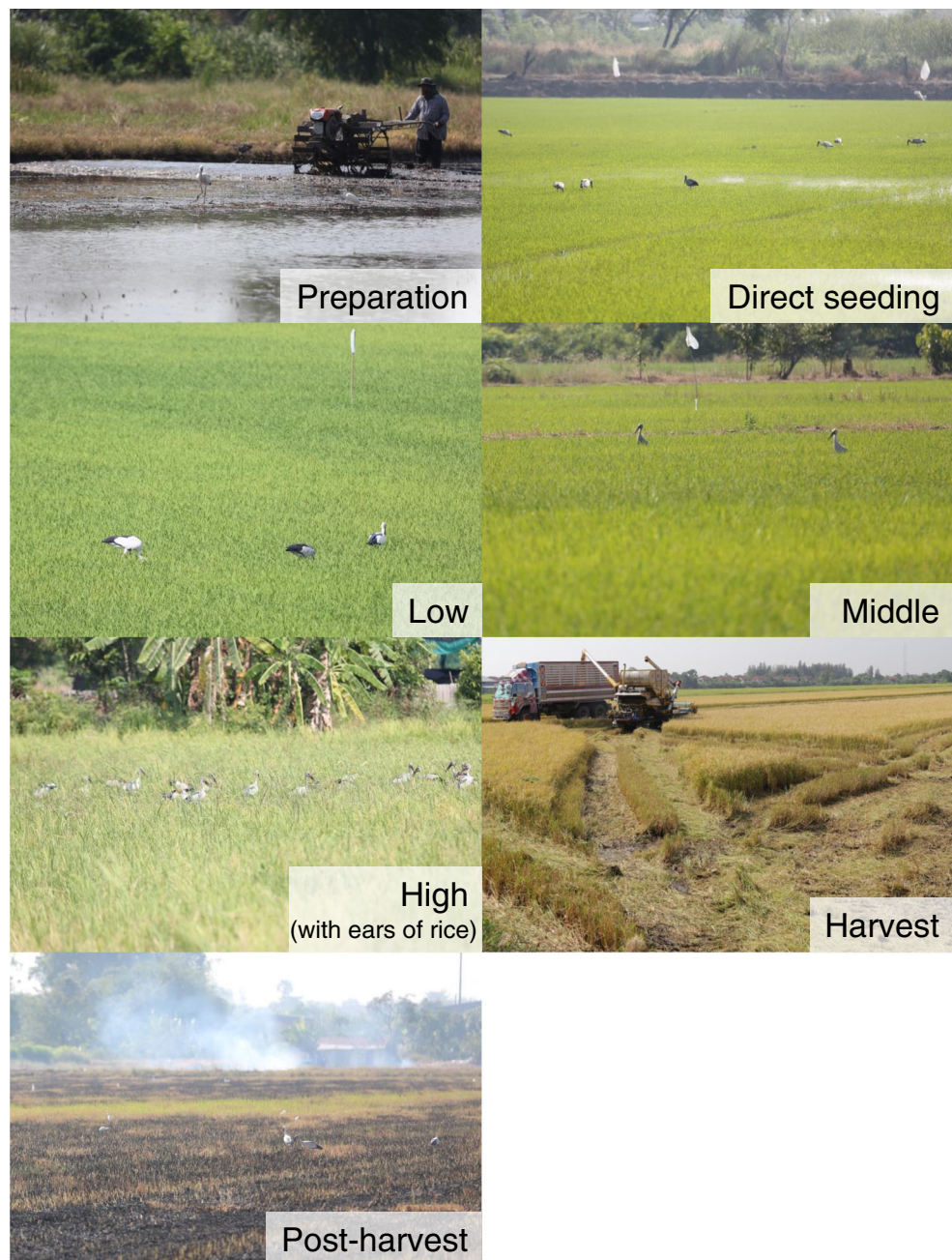
**Fig. 2** Field survey routes and monitored plots and ponds in the study area

landscapes in which we observed the openbills (we used a Casio EX-H20G GPS digital camera).

We also recorded the following pond uses: aquaculture, fish and shrimp ponds; abandoned, ponds resulting from soil excavation in an adjacent lot with no specific use, usually having some floating grasses and/or *Typha* plants; large-scale reservoir, a large deep pool without aquatic plants resulting from large-scale soil excavation; and recreational, landscaped ponds for the recreational use of residents. We verified the purposes and uses of the soils excavated from the ponds when landowners were readily available in the

fields. We conducted this pond use survey for 130 ponds (Fig. 2) out of the 480 ponds extracted in the most recent GIS-based pond map. We also noted the rice growth stages for the rice fields shown in Fig. 3 as follows: preparation; direct seeding; low, approximately 20 cm in height covering the feet and lower leg of Asian openbills; middle, approximately 50 cm in height covering the entire body under the neck of the Asian openbills; high, approximately 80 cm in height, covering almost the entire body of the Asian openbills; harvest; and post-harvest (Fig. 3). Shallow muddy waters were usually present during the preparation and direct seeding

**Fig. 3** Rice growth stages



stages and supplied Asian openbills with frogs and other food. According to the farmers, a small amount of water was also present during the low stage in small hollows in the lots due to recent labor extensive various type of rice lot management along with urbanization and speculative land holdings. During and after the middle stage, the lots were basically dry; after harvest, rice straw was burned (Fig. 3) and insects emerged for openbill consumption. Growth stage validation was conducted in 4 periods: March 2014, June 2014, August 2014, and December 2014. The number of monitored fields varied by period because new development around the fields and road construction sometimes limited accessibility to some fields.

### Interviews with local residents

We conducted semi-structured interviews with local residents at the points shown in Fig. 2. Fifteen interviewees were spatially randomly selected and questions covered issues including the respondents' perceptions of changes in the number of Asian openbills and related land-use issues. We also visited the Bird Conservation Society of Thailand in August 2014 and acquired information on the population trends of Asian openbills and other waterbirds in our study area, as well as the wider scales of the Chao Phraya Delta and all of Thailand and the surrounding migratory countries such as Cambodia and Vietnam.

### Statistical analysis of land uses and Asian openbill distributions

We conducted the following 3 spatial statistical analyses using ESRI ArcGIS version 10.0, Microsoft Excel version 2010, and IBM SPSS Statistics version 22. First, we performed the Kruskal–Wallis test, a non-parametric test, to evaluate the differences in group size among the 5 categories of Asian openbill behavior. Before doing this, we selected “catching food” and “resting” among the 5 categories, because in the case of roosting observation points, we found that Asian openbills stayed on the higher electric pylons during nighttime, sometimes with a population of more than 100. It was occasionally difficult to determine the exact locations for the “moving” category because of the high aerial flying of the openbills. Hence, because of the larger sample sizes and more accurate location data, we chose the “catching food” and “resting” categories for further statistical spatial analysis. Second, we examined the association between group sizes of Asian openbills and surrounding land-use patterns using the Pearson's chi-squared test. The patterns were defined as land-use combination types calculated by cluster analysis using Ward's method of land-use combination ratios within 100-m radius buffers from the observation points of Asian openbills in our line census survey (Appendix Fig. 9). Third, we

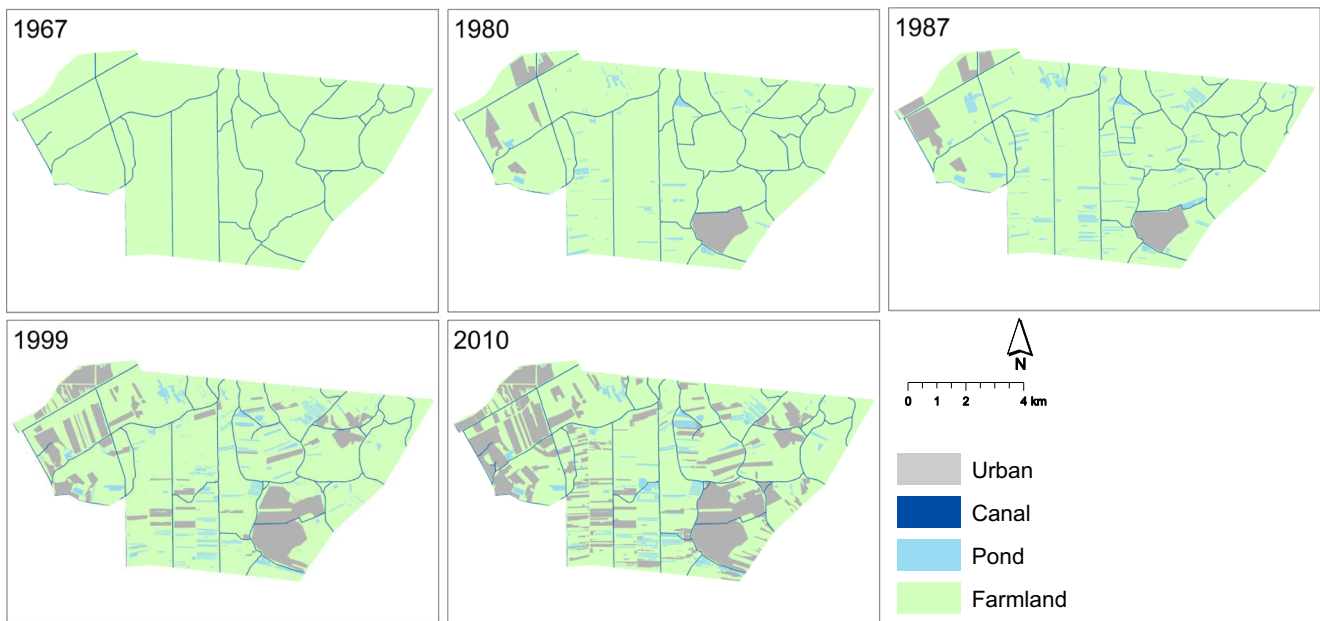
examined the association between Asian openbill observation points and nearby land use types along the entire route of our line census. For this purpose, we conducted binary logistic regression between the presence (or absence) of Asian openbills as bound variables and land-use areas as free variables. We defined land-use area as follows. We segmented the whole census line into 500-m lengths with 100-m buffers from the line; this resulted in the continuous agglomeration of 500 m × 200 m sections. We then calculated land-use combination ratios for each section and set the probability of the presence of the Asian openbills as a dummy variable:  $P = 1$ , the presence of Asian openbills;  $P = 0$ , the absence of Asian openbills. To decide which variables to include in the logistic regression analysis, we referred to the Pearson product-moment correlation to see if any of the variables were correlated (i.e.,  $r > 0.4$ ). We then introduced the variables into a binary logistic regression model. All variables applied in the analysis were tested with the Forward Selection (Likelihood Ratio) process, and the evaluated results were then used to complete the regression model. After the model was constructed, we tested the goodness of fit of the model by using the Hosmer–Lemeshow test.

## Results

### Land-use change

The land use maps of the study area in 1967, 1980, 1987, 1999, and 2010 (Fig. 4) show that both urban areas and the number of ponds increased overall, replacing farmland, mostly rice fields. Of the 130 monitored ponds, 80% were used for aquaculture, 10% were abandoned, 6% were large-scale reservoirs, and the rest were recreational. Recreational ponds were mainly used for viewing and boating and found inside gated subdivisions, and large-scale reservoirs were found in large subdivisions and industrial developments. Interviewees reported that the depth of aquacultural, abandoned, and recreational ponds varied from 1.5 m to 12 m, all sloping relatively gently towards the deepest parts so that trees and riparian plants could grow along the shorelines and in shallow areas, whereas the depth of large-scale reservoirs was sometimes greater than 30 m and the reservoir edges were nearly vertical and not suitable as a riparian ecosystem.

We found that the number of ponds increased from 1980 to 1999 and then decreased from 1999 to 2010 (Fig. 5). Through 1999, more than half of the ponds had almost no trees (Fig. 5). By 2010, however, most ponds had trees, and more than half were either in the medium amount or many tree categories (Fig. 5). The length of the tree line around the pools increased from 1980 through 2010 (Fig. 5). Our field investigation indicated that there were mainly coconut, mango, banana, and other fruit trees in the area. Our interview respondents



**Fig. 4** Land-use maps for 1967, 1980, 1987, 1999, and 2010

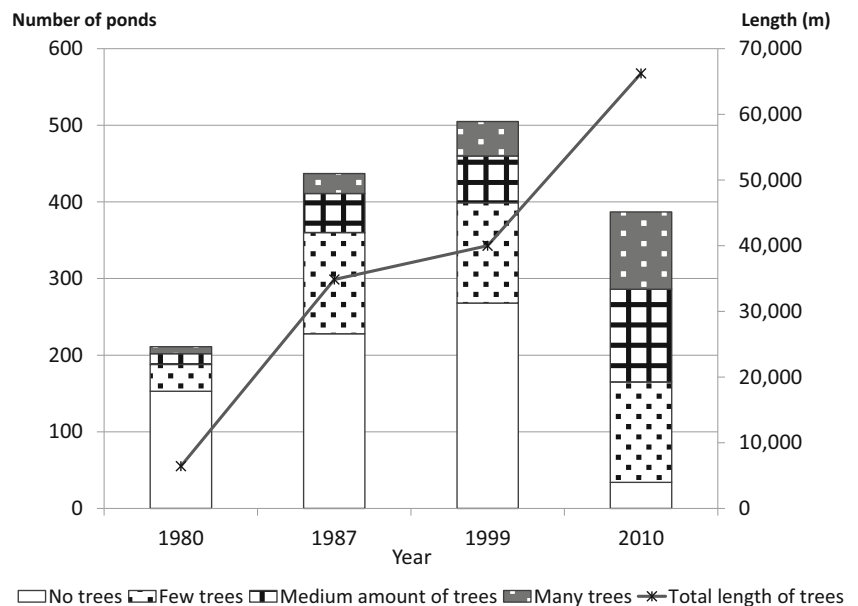
reported that they planted the trees to reinforce the pond banks as well as to grow fruit for their own consumption.

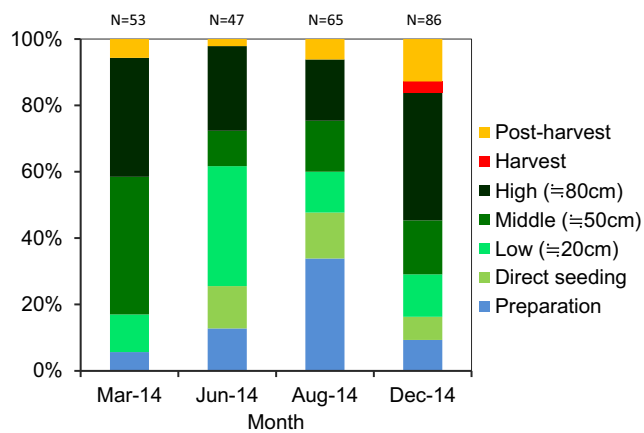
The stages of rice growth in the rice fields of the study area were monitored throughout the year (Fig. 6). The dry season (December 2014) and hot season (March 2014) had higher proportions of growth stages without much water than those of the rainy seasons (June and August 2014), probably because of farmers’ intentions to plan their planting schedules around the availability of irrigation water. The interview respondents confirmed this interpretation. Nevertheless, all of the various rice growth stages were present year round (Fig. 6).

### Spatiotemporal distribution of Asian openbills

We observed the presence of Asian openbills in 307 instances: 148 catching food, 102 resting, 42 moving, 4 roosting, and 11 breeding (see Appendix Fig. 9 for the detailed locations of Asian openbills along with detailed land uses in 2010). Approximately 80% (119 out of 148) of the catching food observations and 96% (98 of 102) of the resting observations had a group size of less than 10 openbills. Furthermore, single and paired Asian openbills seemed to behave and adapt differently to the surrounding land uses, as compared to larger

**Fig. 5** The length and density of trees relative to the number of ponds, 1980–2010





**Fig. 6** Rice growth stage ratios for 4 dates

population groups. Larger population groups tended to mix with other wetland bird species. We therefore defined 4 group sizes for the group size–land use analysis: single or pair ( $N=1-2$ ), small (3–9), medium (10–29), and large (30 or more).

Through our cluster analysis using Ward’s method with a 100-m buffer (from Asian openbill observation points) and surrounding land-use combination ratios, we identified 4 land-use clusters (Table 1). “Urban land use” included mostly built-up areas and roads, that is, urban land use consisting of subdivisions and factories. “Vacant-wetland” included a variety of other uses (wetlands, wastelands, abandoned fields, and speculative vacant land), roads, and some ponds, indicating a transitional area with varied land uses. “Mosaic land use” included a wide range of land uses in roughly equal proportions, that is, a mosaic of both urban and rural land uses. “Rice field” predominantly included rice fields.

We tested associations between group size type and the land use clusters for the catching food and resting behavior categories (Fig. 7). In the catching food category, a group size of 1–2 had almost equal distribution

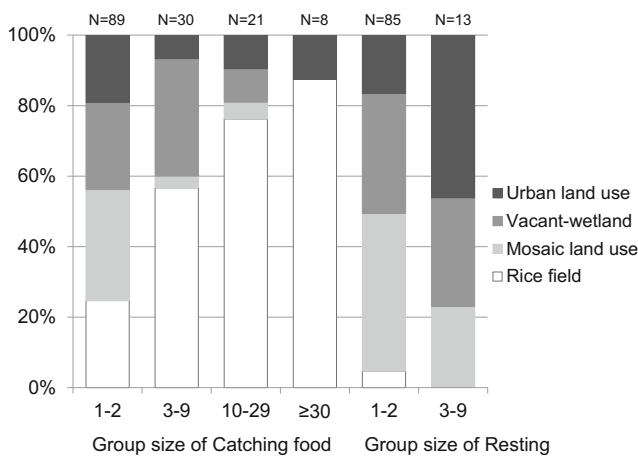
across the 4 clusters. However, as group size increased, the proportion of observations in “Rice field” increased significantly (Pearson’s chi-squared test,  $P < 0.01$ ). In the resting category, the numbers of observations for the larger 2 group sizes (10–29 and  $\geq 30$ ) were 3 and 1, respectively, so we excluded those 2 group sizes from the statistical analysis. There were almost no observations in “Rice field” for either of the smaller group sizes. Moreover, among the other clusters, there were no statistical differences. Thus, catching food was correlated with the presence of rice fields, especially in larger groups, whereas resting behavior was not affected by specific land use. The association of rice growth stage and the presence of Asian openbills is shown in Table 2 for the “catching food” category. Asian openbills tended to use the fields during the earlier stages of rice growth and after harvest, but less so during the high and harvest stages.

We also examined the association between the presence of Asian openbill observation points and surrounding land uses along our census lines. Because of its high multicollinearity, the built-up category was excluded, and the remaining 10 variables were used for the logistic regression analysis. Table 3 summarizes the logistic regression analysis of each season. In the hot season, canals, other, all 3 types of ponds with trees, and rice fields had a positive impact on the probability ( $P$ ) of the presence of the Asian openbill, whereas roads had a negative impact. In the rainy season, canals, other, ponds with few trees and with medium amount of trees, and rice fields had positive impacts on the probability. In the dry season, ponds with few trees and rice fields had positive impacts. In the case where all seasons are combined, canals, other, ponds with few trees and with many trees, and rice fields had positive impacts on the probability of the presence of the Asian openbill, whereas roads had a negative impact. In the case of all seasons except the dry season, canals, other,

**Table 1** Ratio of land use in 4 land-use clusters

| Cluster         | Ratio of land use (%) |       |                 |                  |                     |                   |            |       |                   |       | Frequency |       |
|-----------------|-----------------------|-------|-----------------|------------------|---------------------|-------------------|------------|-------|-------------------|-------|-----------|-------|
|                 | Built-up area         | Canal | Pond (No trees) | Pond (Few trees) | Pond (Medium trees) | Pond (Many trees) | Rice field | Grove | Orchard/Vegetable | Other |           | Road  |
| Urban land use  | 46.88                 | 10.86 | 3.84            | 6.31             | 0.86                | 0.18              | 0.40       | 1.20  | 6.48              | 6.75  | 16.25     | 17.2% |
| Vacant-wetland  | 14.58                 | 6.75  | 0.34            | 2.38             | 0.42                | 2.58              | 6.59       | 1.82  | 1.51              | 46.50 | 16.52     | 28.0% |
| Mosaic land use | 7.56                  | 11.83 | 0.00            | 9.33             | 7.13                | 4.15              | 1.68       | 18.19 | 13.19             | 13.69 | 13.26     | 28.4% |
| Rice field      | 1.73                  | 1.69  | 0.00            | 0.52             | 0.50                | 0.12              | 70.42      | 2.76  | 5.82              | 8.02  | 8.42      | 26.4% |
| Total average   | 14.7%                 | 7.6%  | 0.8%            | 4.5%             | 2.4%                | 2.0%              | 21.0%      | 6.6%  | 6.8%              | 20.2% | 13.4%     |       |





**Fig. 7** Associations between group size and land-use clusters. Land-use clusters are defined in the text and Table 1

ponds without trees, ponds with few trees and with many trees, and rice fields had positive impacts on the probability of the presence of the Asian openbill, whereas roads had a negative impact. The results of the Hosmer–Lemeshow test showed that all of the seasons were relatively highly adaptive to the model. However, in the dry season, the omission error was high (88.9%, Table 4) in the observed group. Moreover, the omission error in all seasons combined (62.6%) was higher than that in all seasons excluding the dry season (56.1%), indicating the existence of factors other than land use for the dry season.

We had 13 reliable responses from our 15 field interviews (see Fig. 8 for the results and locations of the interview surveys; see Appendix Table 5 for the complete list of interviews). In summary, the Asian openbill was reported to be a year-round resident bird since the 1950s. Many respondents stated that there had been a large breeding colony in orchards on the west side of the Lat Krabang Industrial Estate (established in 1978). As the surrounding lands of this estate became more developed, some respondents reported they generally felt there had been an increase in the number of Asian openbills. After completion of the Bangkok Suvarnabhumi International Airport (completed in 2006), this orchard was developed into urban land, and the colony disappeared. The perceptions of Asian openbill population change differed spatially, particularly after the completion of the airport and its

surrounding land developments. In the nearer west side of the Lat Krabang Industrial Estate, informants felt that the number had decreased, whereas informants in remote sites (the western part of the study area) felt it had increased. Most informants welcomed Asian openbills, especially because this bird does not eat agricultural crops but does consume harmful applesnails. Some farmers and pond users replied that they sometimes release all pond water for maintenance of the pond bottom and to dredge sludge. They said that Asian openbills came in large numbers during this period to feed. This type of pond maintenance seems to occur somewhat randomly across the whole area, providing spatially wide opportunities for feeding.

## Discussion

### Long-lasting urban–rural dynamic wetland landscape

This study showed that the wetland mosaic landscape based on inherent pond–fill land diversification in our study area was longstanding. As shown by the maps in Fig. 4, this dynamic landscape was present from at least 1980 and continued through 2010. This type of land development was adaptive to the inherent flood conditions in this continental delta (Hara et al. 2005). The landscape change was also influenced by the cost and availability of fill materials (Hara et al. 2008). In our interviews, landowners stated they obtained the soil used for urban fill from adjoining land. Pond owners also explained that they used excavated soil for nearby developments or sold it to the construction markets as Hara et al. (2008) also reported. If we assume 1 m of fill for all urban developments on the 2010 map (Fig. 4), a soil volume of approximately 1700 m<sup>3</sup>/ha would be needed. This amount is in agreement with the results of Hara et al. (2008). If this fill volume was exclusively extracted from ponds in this area, the average pond depth would be approximately 5.8 m, which is consistent with the interview results. Given the results of both the interviews and the mapping, it appears that most of the urban fill soil was obtained from pond excavation in this area, mostly creating relatively shallow ponds with edges that are suitable for riparian plant growth.

**Table 2** The association between rice growth stage and the presence of Asian openbills

|         | Preparation | Direct seeding | Low | Middle | High | Harvest | After harvest |
|---------|-------------|----------------|-----|--------|------|---------|---------------|
| Absent  | 21          | 15             | 23  | 24     | 60   | 3       | 12            |
| Present | 15          | 3              | 11  | 6      | 3    | 0       | 7             |

**Table 3** Summary of logistic regression analysis

| Season           | Variable Name        | B                       | p-Value                | Odds ratio            | Hosmer-Lemeshow test |                       |       |
|------------------|----------------------|-------------------------|------------------------|-----------------------|----------------------|-----------------------|-------|
| Hot              | Canal                | $2.534 \times 10^{-4}$  | $1.1 \times 10^{-7}$   | 1.000                 | 0.995                |                       |       |
|                  | Other                | $0.318 \times 10^{-4}$  | 0.007                  | 1.000                 |                      |                       |       |
|                  | Pond(Few trees)      | $1.372 \times 10^{-4}$  | 0.043                  | 1.000                 |                      |                       |       |
|                  | Pond(Many trees)     | $1.990 \times 10^{-4}$  | $2.2 \times 10^{-4}$   | 1.000                 |                      |                       |       |
|                  | Pond(Medium trees)   | $2.939 \times 10^{-4}$  | 0.035                  | 1.000                 |                      |                       |       |
|                  | Rice field           | $0.463 \times 10^{-4}$  | 0.014                  | 1.000                 |                      |                       |       |
|                  | Road                 | $-0.913 \times 10^{-4}$ | 0.001                  | 1.000                 |                      |                       |       |
|                  | Constant             | -2.744                  | $3.6 \times 10^{-5}$   | 0.064                 |                      |                       |       |
| Rainy            | Canal                | $3.298 \times 10^{-4}$  | $3.0 \times 10^{-9}$   | 1.000                 | 0.948                |                       |       |
|                  | Other                | $0.430 \times 10^{-4}$  | 0.002                  | 1.000                 |                      |                       |       |
|                  | Pond(Few trees)      | $1.562 \times 10^{-4}$  | 0.004                  | 1.000                 |                      |                       |       |
|                  | Pond(Medium trees)   | $1.828 \times 10^{-4}$  | 0.014                  | 1.000                 |                      |                       |       |
|                  | Rice field           | $0.673 \times 10^{-4}$  | $2.2 \times 10^{-7}$   | 1.000                 |                      |                       |       |
|                  | Constant             | -5.362                  | $1.8 \times 10^{-11}$  | 0.005                 |                      |                       |       |
|                  | Dry                  | Pond(Few trees)         | $2.627 \times 10^{-4}$ | $4.0 \times 10^{-4}$  |                      | 1.000                 | 0.710 |
|                  |                      | Rice field              | $0.469 \times 10^{-4}$ | 0.003                 |                      | 1.000                 |       |
| Constant         |                      | -4.003                  | $0.5 \times 10^{-10}$  | 0.018                 |                      |                       |       |
| All              | Canal                | $2.329 \times 10^{-4}$  | $1.0 \times 10^{-14}$  | 1.000                 | 0.814                |                       |       |
|                  | Other                | $0.253 \times 10^{-4}$  | 0.001                  | 1.000                 |                      |                       |       |
|                  | Pond(Few trees)      | $1.633 \times 10^{-4}$  | $7.1 \times 10^{-7}$   | 1.000                 |                      |                       |       |
|                  | Pond(Many trees)     | $1.141 \times 10^{-4}$  | $1.5 \times 10^{-4}$   | 1.000                 |                      |                       |       |
|                  | Rice field           | $0.428 \times 10^{-4}$  | $7.0 \times 10^{-8}$   | 1.000                 |                      |                       |       |
|                  | Road                 | $-0.613 \times 10^{-4}$ | $8.8 \times 10^{-6}$   | 1.000                 |                      |                       |       |
|                  | Constant             | -2.969                  | $1.5 \times 10^{-10}$  | 0.051                 |                      |                       |       |
|                  | All (except for Dry) | Canal                   | $2.520 \times 10^{-4}$ | $1.6 \times 10^{-13}$ |                      | $1.6 \times 10^{-13}$ | 0.735 |
| Other            |                      | $0.304 \times 10^{-4}$  | $4.3 \times 10^{-4}$   | $4.3 \times 10^{-4}$  |                      |                       |       |
| Pond(No trees)   |                      | $1.270 \times 10^{-4}$  | 0.143                  | 0.143                 |                      |                       |       |
| Pond(Few trees)  |                      | $1.763 \times 10^{-4}$  | $6.2 \times 10^{-6}$   | $6.2 \times 10^{-6}$  |                      |                       |       |
| Pond(Many trees) |                      | $1.101 \times 10^{-4}$  | $4.5 \times 10^{-4}$   | $4.5 \times 10^{-4}$  |                      |                       |       |
| Rice field       |                      | $0.488 \times 10^{-4}$  | $2.6 \times 10^{-7}$   | $2.6 \times 10^{-7}$  |                      |                       |       |
| Road             |                      | $-0.576 \times 10^{-4}$ | $2.1 \times 10^{-4}$   | $2.1 \times 10^{-4}$  |                      |                       |       |
| Constant         |                      | -3.174                  | $4.4 \times 10^{-9}$   | $4.4 \times 10^{-9}$  |                      |                       |       |

We did observe, however, that some ponds were filled with construction debris. This indicated that future land development may proceed using fill into the ponds, causing environmental problems such as water pollution and loss of flood retention capacity (Hara et al. 2005; Honda et al. 2010). Indeed, some pond owners mentioned that they wanted to sell but cannot because fill cost was high and buyers are currently scarce; hence, these owners continued with aquaculture in the ponds, which was more profitable than abandoning the pond and land. However, it is also unlikely that all of the land, including ponds developed by speculators, will become completely developed in the future. Because the land

development pattern in the urban fringe of Bangkok is highly variable and unplanned (Hara et al. 2010), leapfrog developments along major transportation routes and private dead-end roads are common and involve canal fragmentation (Davivongs et al. 2012). Trends of population growth and urbanization also are uncertain. For example, after the large floods of 2011, many foreign and domestic industrial companies began to look for safer locations for factories to avoid future flooding risk. New industrial estate development has been active in the delta rim on relatively higher landforms, whereas at the Lat Krabang Industrial Estate, a new flood protection wall was constructed. Thus, this continental delta

**Table 4** Logistic model accuracy and error

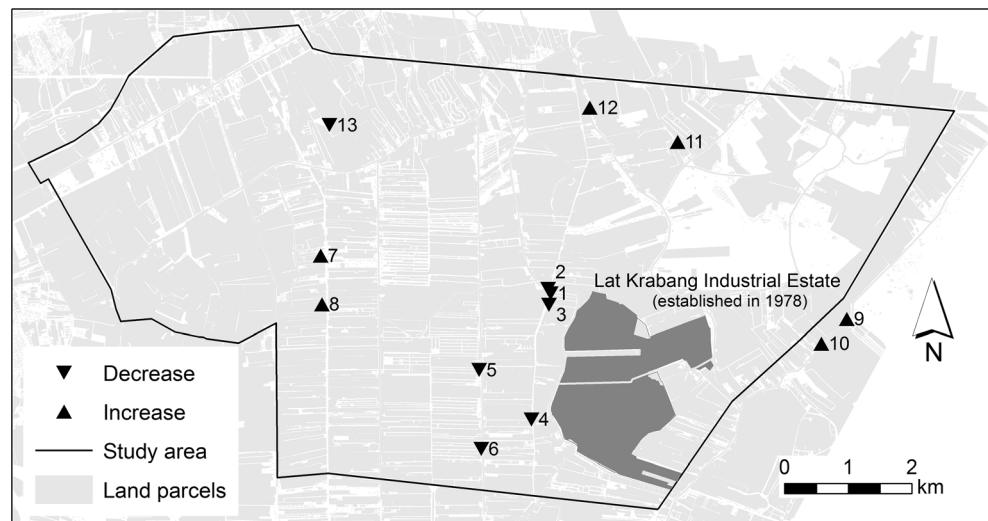
| Season               |           | Logistic model |         | Accuracy (%) | Error (%) |
|----------------------|-----------|----------------|---------|--------------|-----------|
|                      |           | Absent         | Present |              |           |
| Hot                  | Absent    | 159            | 11      | 93.5         | 6.5       |
|                      | Present   | 18             | 24      | 57.1         | 42.9      |
|                      | Total (%) |                |         | 86.3         | 13.7      |
| Rainy                | Absent    | 214            | 7       | 96.8         | 3.2       |
|                      | Present   | 25             | 15      | 37.5         | 62.5      |
|                      | Total (%) |                |         | 87.7         | 12.3      |
| Dry                  | Absent    | 128            | 2       | 98.5         | 1.5       |
|                      | Present   | 8              | 1       | 11.1         | 88.9      |
|                      | Total (%) |                |         | 92.8         | 7.2       |
| All                  | Absent    | 508            | 13      | 97.5         | 2.5       |
|                      | Present   | 57             | 34      | 37.4         | 62.6      |
|                      | Total (%) |                |         | 88.6         | 11.4      |
| All (except for Dry) | Absent    | 375            | 16      | 95.9         | 4.1       |
|                      | Present   | 46             | 36      | 43.9         | 56.1      |
|                      | Total (%) |                |         | 86.9         | 13.1      |

still has a high capacity as an urban hinterland to accept new urban and agricultural land development and the associated landform transformations, which will continue to induce extensive wet landscape mosaics.

In the long term, population increases in the Bangkok area may not be a permanent trend. Urbanization pressure may peak and urban shrinkage may become a real phenomenon. Even under this situation, the remaining rice fields and ponds may still remain as important wetland mosaic components.

The history of urban fringe land use in rice-growing areas in Japan provides data supporting the notion that predicting land-use changes on the premise of “one-way urbanization” is unrealistic. Previous research has shown that urban–rural land-use mixing proceeds without effective planning measures (Ichikawa et al. 2006; Saizen et al. 2006). Japan is currently entering a depopulation stage and facing shrinkage in many cities. Yokohari and Bolthouse (2011) promoted the maximization of ecosystem service provision of the fragmented urban

**Fig. 8** The change in Asian openbill numbers as noted by interviewees. Numbers correspond to the interviewee’s ID in Appendix Table 5



fringe open spaces, particularly to provide cultural services to local residents. This urban shrinkage–ecosystem service issue is also very common in other developed countries (Haase 2013). Thus, in the future, urbanization pressure may decrease in the Bangkok area, and agricultural and other types of open spaces in the urban fringe will not be developed.

### Asian openbill habitat adaptation

This study revealed that the Asian openbill was adaptive to the dynamic wet landscape mosaics in this area. Among these wet landscape mosaic components (Fig. 7 and Table 3), rice fields can provide a major source of food for the Asian openbill. The importance of ecosystem services provided by rice fields has already been recognized (e.g., Natuhara 2013), in particular for wetland bird species (Amano et al. 2008). However, these studies mainly described rice fields as seasonally limited surrogate wet habitats as a source of food for wetland birds. For example, Endo and Nagata (2013) reported that the reintroduced Japanese crested ibis (*Nipponia nippon*) on Sado Island, Japan adapted to rice fields as a core food source as well as obtaining food from surrounding habitats during the annual single-cropping rice cultivation calendar. Masero et al. (2011) reported that, in the west coastal area of the Iberian Peninsula, as a substitute for natural large-scale wetlands, rice fields have become a major habitat for long-distance migratory shorebirds, particularly during winter pooling.

In common with those studies, the importance of rice fields as a major food source was also found in this study. However, a single-cropping rice calendar is used in the mid-latitude areas of those studies, which restricts the annual spatiotemporal dynamics of having rice fields in various growing stages at any given time, such as was seen in our study area (Fig. 6), and which can provide a continuous source of food throughout the year for Asian openbills (Table 2), such as frogs and snails in watered lots (during the preparation and direct seeding stages) and insects in dry lots (during the low, middle, and after harvest stages), as was seen in our study area. The variety of rice-growing stages in the dry season (December 14 in Fig. 6) and the relatively high omission errors in the dry season (Table 4) also probably indicate the important function of rice fields in various growth stages in terms of the water environment and rice height in supporting the presence of Asian openbills in this area. Sundar (2004) investigated black-necked storks (*Ephippiorhynchus asiaticus*) and their habitat adaptation to mixed agriculture-dominated landscapes in an alluvial plain of the Ganges with

similar tropical monsoonal climatic and geographic land conditions and noted the importance of mixed wet landscapes, including annually watered canals, flooded rice fields, and surrounding environments, but still considered natural remaining wetlands to be the most vital habitat component.

In our study, we evaluated long-term landscape transformations (Figs. 4 and 5) and found that wet landscape mosaic components were interrelated through landform transformation via surface soil movements, ensuring further various micro-scale wet landscape components, including rice fields, canals, ponds and their surrounding trees, and other urban land uses. Although having a variety of growing stages at any given time in rice fields can provide major sources of food for Asian openbills, other wet landscape components induced by inherent landform transformations can also provide additional foraging and resting places for Asian openbills. We found that the most ponds in the study area were used for aquaculture and had dynamic water level management. They were generally shallow (a few meters deep) and were suitable as habitat for some riparian plants as a result of the way they were originally excavated. In addition, the number of trees surrounding the ponds increased over time (Fig. 5), providing a year-round source of supplemental food and resting habitats for the openbills. Year-round irrigation canals were also shown to be suitable for Asian openbill inhabitation (Table 3). The mosaic landscape in the study area should persist for the foreseeable future; hence, we expect that Asian openbills should remain in the area indefinitely and it seems to have become a resident bird in the study area.

This trend may have begun a long time ago in conjunction with human habitation of the Chao Phraya Delta and the resulting intensive canal and fill development since the middle of the nineteenth century (Tanabe 1977). Madoc (1950) reported that in 1949 there was the only 1 large nesting colony at Wat Phai Lom (on the Chao Phraya's east bank), Samkhok District, upstream of Pathumthani Province (approximately 40 km northwest from our study area) in this delta region. McClure and Kwanyuen (1973) also reported the existence of this colony, and noted that the Asian openbills were purposely disturbed by local residents because they destroyed farmers' orchard trees and other crops. Round (2008) noted that, together with these human disturbances and perhaps the removal of trees and other land transformation, Asian openbills were distributed from this large colony into other smaller colonies. Expansion of the golden applesnail has helped the current adaptation trend because Asian openbills have functioned

as a good biological control agent for this snail (Sawangproh and Poonswad 2010). Our interview survey results (Fig. 8) also supported this local-scale diffusion of Asian openbill habitats into the human-induced wetland mosaics investigated in this study. Thus, long-term Asian openbill inhabitation in this area seems to be guaranteed by its dynamic wet landscape mosaics. Nevertheless, we need to continuously monitor this landscape mosaic and Asian openbill adaptations in the future because of other possible threats such as a drastic increase of pesticide use and changing relationships with other bird species, as noted by Buij and Croes (2013) in the case of the Lake Chad Basin.

Our study methods, which included detailed spatio-temporal wet landscape monitoring combined with the investigation of an indicator species, could be applicable to research on other Asian deltas facing landscape changes, especially from regional planning perspectives, as well as other delta landscapes such as in the Netherlands where surface land transformation is inherently essential for human habitation (Hara et al. 2014). In the Yellow River Delta, Li et al. (2011) surveyed waterbird community composition changes across the natural and restored wetland landscape mosaic, and highlighted the conservation benefits of restoring smaller artificial wetland components in improving the ecological integrity of the wider wetland landscape mosaic for waterbird populations. At the same time, Li et al. (2013) revealed that artificial wetlands provide a secondary role in habitat conservation. Fisher et al. (2011) discussed the role that species-led management for the benefit of biodiversity in cultural landscapes can play in the delivery of wider ecosystem services in lowland wetlands in the United Kingdom and showed how successful delivery of species-led conservation through management interventions relies on practices that can affect greenhouse gas fluxes, water quality and regulation, and cultural benefits. In the case of the Chao Phraya Delta, management of landscape mosaics led by restorations targeting the Asian openbill may be applicable not only to the conservation of wetland ecosystems but also to the co-establishment of sustainable rice production and water regulating services of fragmented wetland landscapes. Naito et al. (2014) provided a successful referential case in cultural landscape planning and management using the reintroduced Oriental white stork (*Ciconia boyciana*) as an indicator species. They found that regional promotion of organic-based rice farming to provide a core habitat for this bird can co-benefit local farmers and the economy through higher prices for the rice produced from these rice fields

and environmentally friendly labelling using the bird as a symbol on the label. We observed government-sponsored notices noting the importance of Asian openbills in some wetland areas within industrial estates in our study area, but the openbill's importance still is seemingly not well recognized by local residents. Distribution of scientific information about the value of Asian openbills and other micro-scale ecosystem components in relation to rice fields, ponds, and other wet landscape components and management methods could help people gradually maximize ecosystem services so that the local ecosystem and economy become sustainable in this deltaic complex and dynamic wetland mosaic landscape.

## Conclusions

This study showed that the combination of pond and fill land development was inherent in the continental Chao Phraya Delta, and it induced a dynamic wet landscape mosaic in the urban fringe of Bangkok. This landscape provided good habitat for the Asian openbill, with feeding areas in the remaining rice fields and emerging ponds, and resting areas in the trees around the ponds. These landscapes and Asian openbill habitats were both dynamic and longstanding. Future research topics should include a more time-intensive and spatially wider monitoring of the wet landscape components, including rice fields in various growing stages and managed ponds by high-resolution SAR and UAV image analyses. In addition, additional continuous line census and direct telemetry tracking of Asian openbills should be conducted. These investigations will provide clearer relationships between wet landscape mosaic dynamics and Asian openbill adaptations as an important example of human-induced wetland ecosystem services.

**Acknowledgements** This research was funded partially by a grant from the Japan Society for the Promotion of Science through the Funding Program for Next Generation World-Leading Researchers (NEXT Program: GZ005), initiated by the Council for Science and Technology Policy; by a Grant-in-Aid for Scientific Research (26850221) from the Japanese Ministry of Education, Culture, Sports, Science and Technology; by the Takahashi Industrial and Economic Research Foundation; and by the Shimizu Institute of Technology, Japan. We thank students and staff at the Department of Landscape Architecture, Chulalongkorn University, who helped with our field survey. We also thank the local residents who participated in our interviews, and the staff at Bussaba Bangkok Hotel, our comfortable home during field research. We thank Dr. Kaset Sutasha and other research staff at the Bird Conservation Society of Thailand for their valuable suggestions.

## Appendix 1

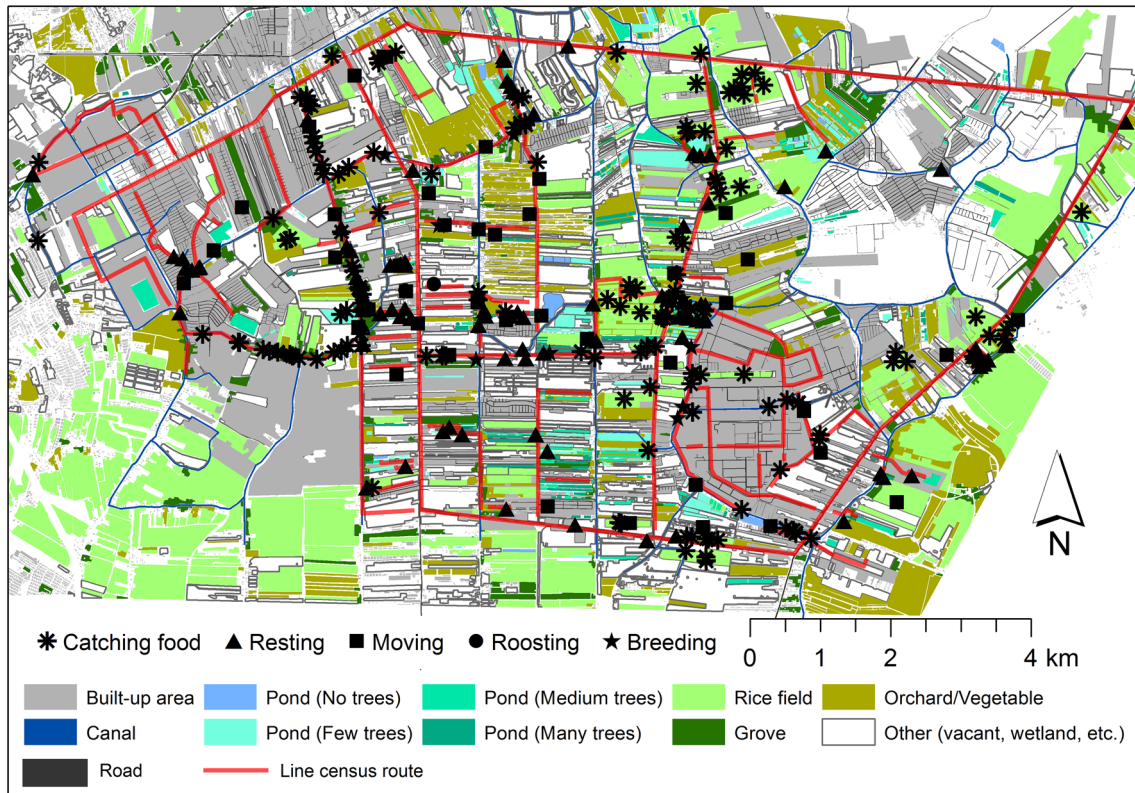


Fig. 9 Asian openbill distribution by behavior category

**Appendix 2**

**Table 5** Complete list of interviews

| ID No.  | 1                                | 2                    | 3   | 4   | 5                  | 6   | 7                     | 8                     | 9                    | 10                   | 11                    | 12                   | 13   |
|---|----------------------------------|----------------------|---|---|--------------------|---|-----------------------|-----------------------|----------------------|----------------------|-----------------------|----------------------|--|
| Age   | 31                               | 50                   | 53  | 45  | 51                 | 65  | 62, 57                | 40                    | 35                   | 67                   | 19                    | 50                   | 74   |
| Gender  | Male                             | Male                 | Female                                      | Male                                      | Male               | Male                                      | Female                | Female                | Male                 | Male                 | Male                  | Male                 | Male   |
| Childhood Land type   | 1985–1995 Fishpond               | 1966–1976 Rice field | 1963–1973 Fishpond                          | 1971–1981 Fishpond                        | 1965–1975 Fishpond | 1951–1961 Fishpond                        | 1954–1964 Coffee shop | 1976–1986 Coffee shop | 1981–1991 Rice field | 1949–1959 Rice field | 1997–2007 Shrimp pond | 1966–1976 Rice field | 1942–1952 Rice, Fish, Fruit                    |
| Land ownership  | No                               | Yes                  | No  | No  | Yes                | Yes                                       | Yes                   | No                    | No                   | No                   | Yes                   | No                   | Fruits: yes<br>Fishpond: yes<br>Rice field: no |
| Since when have you managed this land or lived here?  | 1994                             | 1964                 | 2000  | 1997                                      | 1980               | 1949                                      | 1986                  | 2009                  | 1979                 | 1947                 | 2004                  | 1964                 | 1954   |
| During your childhood, did the Asian openbill stay in this area all year round?   | Yes                              | Yes                  | Yes   | Yes                                       | Yes                | No  | N/A                   | N/A                   | Yes                  | Yes                  | Yes                   | Not observed         | Yes  |
| Has the number of Asian openbills increased now as compared to your childhood days around this pond (paddy)?                        | Decreased                        | Decreased            | Decreased                                   | Decreased                                 | Decreased          | Decreased                                 | Increased             | Increased             | Increased            | Increased            | Increased             | Increased            | Decreased                                      |
| Have you ever seen a colony of Asian openbills around this pond (paddy)?  | Yes*                             | Yes**                | Yes***                                      | No  | No                 | No  | No                    | No                    | No                   | No                   | No                    | No                   | No   |
| At what location does (did) the Asian openbill use this area for nesting?   | Woodland in the development area | Woodland, orchard    | Woodland                                    | Back of Industrial Estate                 | Back of factories  | Back of factories                         | N/A                   | N/A                   | Back of factories    | Near factories       | Pylons                | Lotus pond           | N/A  |
| Do you feel the number of Asian openbills has increased since the factories were built in the Lad Krabang Industrial Estate (1980)? | N/A                              | Decreased            | N/A   | Birds arrived after building of factories | N/A                | Birds arrived after building of factories | N/A                   | Not observed          | N/A                  | Not observed         | N/A                   | N/A                  | Not observed                                   |
| Do you feel the number of Asian openbills has increased since housing was constructed in the Lad Krabang Industrial Estate (1999)?  | Decreased                        | Decreased            | Decreased                                   | Decreased                                 | No difference      | Decreased                                 | N/A                   | Not observed          | N/A                  | Not observed         | N/A                   | Decreased            | Decreased                                      |
| Did the number of Asian openbills fluctuate before and after the new airport opened?  | N/A                              | Yes                  | Unknown (land development at the same time) | Yes (decreased)                           | Yes (decreased)    | Yes (decreased)                           | No                    | Not observed          | No                   | N/A                  | Unknown               | Yes (decreased)      | Yes (decreased)                                |

Table 5 (continued)

| ID No.   | 1  | 2                       | 3                               | 4              | 5                | 6           | 7                | 8           | 9                           | 10          | 11             | 12                     | 13         |
|--|--|-------------------------|---------------------------------|----------------|------------------|-------------|------------------|-------------|-----------------------------|-------------|----------------|------------------------|------------|
| Do you plan on taking any measures concerning the Asian openbill in the future?                  | N/A  | No                      | No                              | No             | No               | N/A         | N/A              | N/A         | No                          | No          | No             | No                     | No         |
| Are there advantages or disadvantages related to the Asian openbill coming to this pond (paddy)? | Advantages   | N/A                     | Advantages                      | Advantages     | Advantages       | Advantages  | N/A              | N/A         | Advantages                  | Advantages  | Advantages     | Advantages             | Advantages |
| How many times a year do you disconnect the water to this pond (paddy)?                          | Every 7 months   | 2.5 times a year        | Fishing: 2 years every 7 months | Every 8 months | Once a year      | Once a year | No               | No          | Twice a year                | Once a year | Every 3 months | Twice a year           | No         |
| How long do you maintain the dry pond?   | If raining, 2–3 days if dry, depends on the water schedule | Rice cultivation period | N/A                             | No             | 10–30 days       | 2 weeks     | No               | No          | Depends on water conditions | 1 week      | Unknown        | Rice field schedule    | No         |
| How do you manage the water level?   | Pump   | Pump                    | Pump                            | Pump, pipe-out | Pipe in/pump out | Pump, pipe  | Pipe, small pump | Do not pump | Canal, pipe, water gate     | Pump, pipe  | Pipe, pump     | Pipe, water gate, pump | Pump       |
| How deep is this pond (paddy)?   | 2–3 m  | Rice field              | 1.8–2.0 m                       | 12 m           | 2 m              | 1.5–1.6 m   | 10 m             | Unknown     | Rice field                  | 1.5 m       | 1.2–1.5 m      | Rice field             | 3 m        |

\*There was a colony in the back of an old rice field, but the field changed to urban land use 3 years ago

\*\*There was a large nesting group in an old woodland before the Suvarnabhumi International Airport was built

\*\*\*There was a colony in the woodland in the back of the pond, but the area changed to urban land use 9 years ago



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