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Population characteristics of giant reed (*Arundo donax* L.) in cultivated and naturalized habitats

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ABSTRACT

In the present study, we analyzed the variability among naturalized and cultivated giant reed (*Arundo donax* L.) populations in terms of density, morphology and primary production along the prevailing environmental gradient in Nile Delta, Egypt. For this purpose, a sampling was carried out in homogeneous and monospecific *A. donax* stands in Nile Delta. The samples were collected to represent the cultivated populations (planted habitat) and the naturalized populations in four habitats (canal banks, waste lands, road and railway sides). Each habitat was represented by 3 stands; and in each stand, density, morphology and biomass were recorded using five randomly distributed quadrats (each of 0.5×0.5 m). The results had indicated a significant variation in density, morphological and biomass parameters between naturalized and cultivated populations. Generally, naturalized populations along the railway and road sides (the less moist habitats) had the minimum values for most measured population parameters, while the cultivated populations (the moistest habitat) had the maximum. The dependence of shoot height, number of branches and panicle length on shoot density indicated the density-size effects. Density, morphology and biomass of *A. donax* were correlated significantly with some soil properties such as salinity, pH, organic matter and nitrogen. The regression technique was applied to develop equations for predicting the biomass of *A. donax* shoots from more easily determined shoot height and shoot basal diameter. These methods were time-saving, so the equations might be useful in evaluating management techniques which were used for monitoring *A. donax*.

1. Introduction

Giant reed (*Arundo donax* L.) is a robust erect perennial rhizomatous grass species reaching up to 14 m height under optimal growth conditions and grows in many clumps (Alshaal et al., 2015). It is characterized by rapid growth rate up to 10 cm per day (Perdue, 1958); thus it is the fastest growing herbaceous grass on the earth (Palmer et al., 2014). It has also a high biomass production, a tendency toward community dominance in many habitats and there will be a tolerance to a wide range of environmental conditions (Dudley, 2000). *A. donax* is usually found along river banks, creeks and generally in moist soils, but it grows also successfully on relatively dry and infertile soils such as road sides (Günes and Saygin, 1996; Sharma et al., 1998). *A. donax* was introduced to Egypt in 1761 (c.f. Shaltout, 2014). Nowadays, it is recorded as a naturalized species along canals, road sides, railways and waste lands in the Nile region, oases of the Western Desert, Mediterranean coastal strip, Sinai and all the desert of Egypt (El-Sheikh, 1996; Boulos, 2009). Many studies are carried out on its ecology, biology, primary production, nutrient dynamics, phytoremediation, physiology, invasion, bioenergy, reproduction, modeling, demography and soil condition. However, to the authors' knowledge, so far no studies have been carried out to analyze the variability among its naturalized and cultivated populations in terms of their density, morphology and primary production.

Density, morphometric and biomass analyses are important parameters in evaluating the plant growth and development (Watson, 1990; Eid et al., 2010a,b, 2012; Shaltout et al., 2010). The above analyses are also useful for evaluating population dynamics and rates of spread in response to environmental factors for a clonal species such as *A. donax* (Decruyenaere and Holt, 2005). Environmental factors are of paramount importance to plant establishment and can vary widely even within a specific habitat type (Quinn and Holt, 2008). Some previous studies have focused on the effect of some soil properties such as nitrogen, pH, salinity, organic mat-

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ter and moisture on the structure of *A. donax* stands (Varanini and Pinton, 2001; Coffman, 2007; Palmer et al., 2014).

The present study aims at comparing between naturalized and cultivated giant reed populations in terms of their density, morphology and primary production. It aims at developing regression equations for predicting *A. donax* phytomass and it also aims at evaluating which ones of soil properties which are more effective in its growth. Our hypothesis is: density, morphology and biomass of *A. donax* vary between the cultivated and naturalized populations along the prevailing environmental gradient in Nile Delta, Egypt.

2. Material and methods

2.1. Study area

The study area is part of Nile Delta that is bounded by the two branches of the Nile (Rosetta to the west and Damietta to the east). According to the map of the world distribution of arid regions (UNESCO, 1977), the north part of Nile Delta lies in the arid region, while the southern part lies in the hyper-arid region. The climatic conditions are warm summers (20–30 °C) and mild winters (≥10 °C). The long-term annual mean air temperature of Nile Delta decreased from 20.7 °C at the north to 19.9 °C at its middle. The relative humidity is decreased in the same direction from 69 to 65%. The average daily evaporation is varied between 4.6 mm day^{-1} at the north and 6.8 mm day^{-1} at the middle. This is associated with an inverse gradient of annual precipitation which varied between 175.2 mm $year^{-1}$ at the north and 56.9 mm $year^{-1}$ at the middle (EMA, 1980).

2.2. Plant sampling

Sampling was carried out at 9 sites in Gharbia Governorate during August 2014 and Kafr El-Sheikh Governorate during September 2014 (Fig. 1). Homogeneous and monospecific stands of *A. donax* were chosen to represent the cultivated populations (planted habitat) and the naturalized populations in four ruderal habitats (canal banks, road sides, waste lands, railway sides). Cultivated populations represented the planted population which was cultivated for roofing material, erosion control, windbreak, baskets and fishing canes. Its fertilizer application was 100/40/100 kg ha^{-1} N/P/K, irrigated twice monthly and harvested once a year during autumn. The 4 ruderal habitats were arranged according to their soil moisture availability as follows (El-Sheikh, 1996): canal banks > waste lands > road sides > railway sides. The habitats of road and railway sides provided an exceptional type of disturbed habitat which were subject to greater stress due to treading, soil compaction, mowing or crushing of tall vegetation, herbicide application, local pollution, soil and rock addition related to slumping and rock falls (El-Sheikh, 1996). Each habitat was represented by three stands and in each stand, density, morphology and biomass which were recorded using 5 randomly distributed quadrats (each of 0.5 × 0.5 m). All of *A. donax* shoots within a sampled quadrat were cut off at the ground level and weighted to give the total above-ground fresh weight (kg FW m^{-2}) (data not presented). The number of flowering and non-flowering *A. donax* shoots per m^2 and branches per shoot were counted. Ten shoots randomly chosen and taken from each quadrat (50 individuals per stand and 150 individuals per habitat) to represent the shoot height variations and transferred to the laboratory in polyethylene bags. Shoot height (stem height + panicle length), number of leaves, shoot basal diameter (at the first complete internode above the basal cut surface) and panicle length were measured. Leaf area (single sided) was measured using a leaf area-meter (Dynamax AM 300). After that, *A. donax* shoots were separated into panicles, leaves and stems, and were cut into fragments of 5 cm length and oven-dried at 105 °C for one week until constant weight. The average dry matter of the shoots was calculated (g $shoot^{-1}$) and multiplied by the number of shoots per m^2 to give the total above-ground biomass (kg DM m^{-2}). Proportional biomass allocation was calculated as the biomass of a specific tissue divided by the total biomass. Flowering ratio was calculated as the number of flowering shoots divided by the total number of shoots (shoot m^{-2}).

2.3. Soil sampling

In each stand, a composite soil sample was collected as a profile from 5 holes, each of 30 cm depth. The soil samples were air dried and passed through a 2 mm sieve to separate gravel and debris before analyses. Soil-water extracts at 1:5 (w/w) were prepared for the determination of pH and salinity. Subsequently, P, Ca, Mg, Na, K, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn contents were extracted

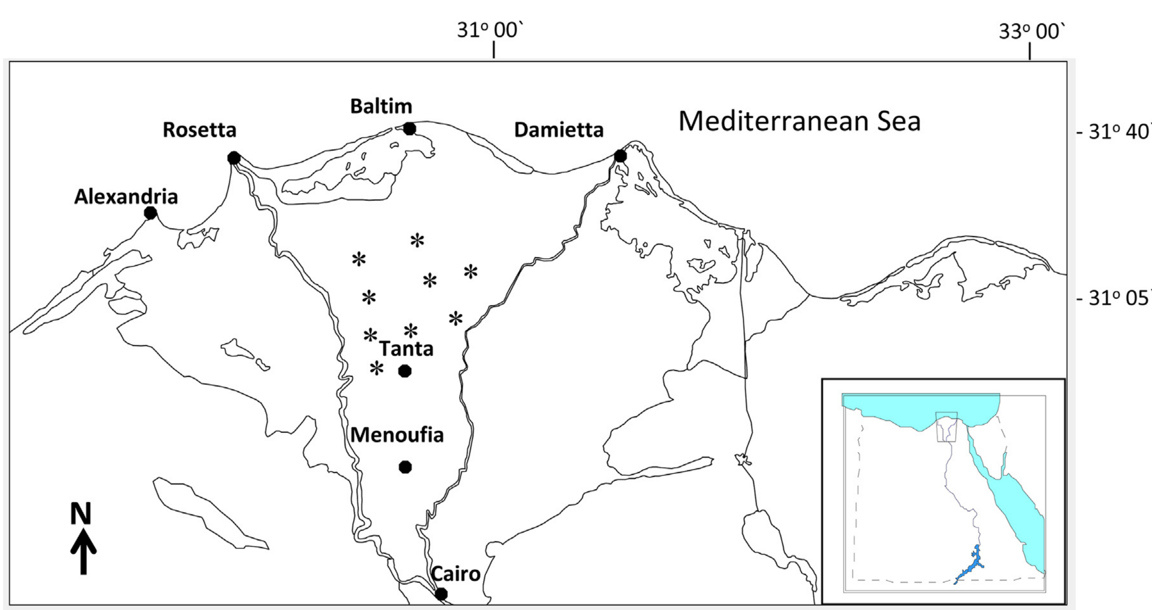

Fig. 1. Map of Nile Delta (Egypt) indicating the locations of the 9 sampling sites (*).

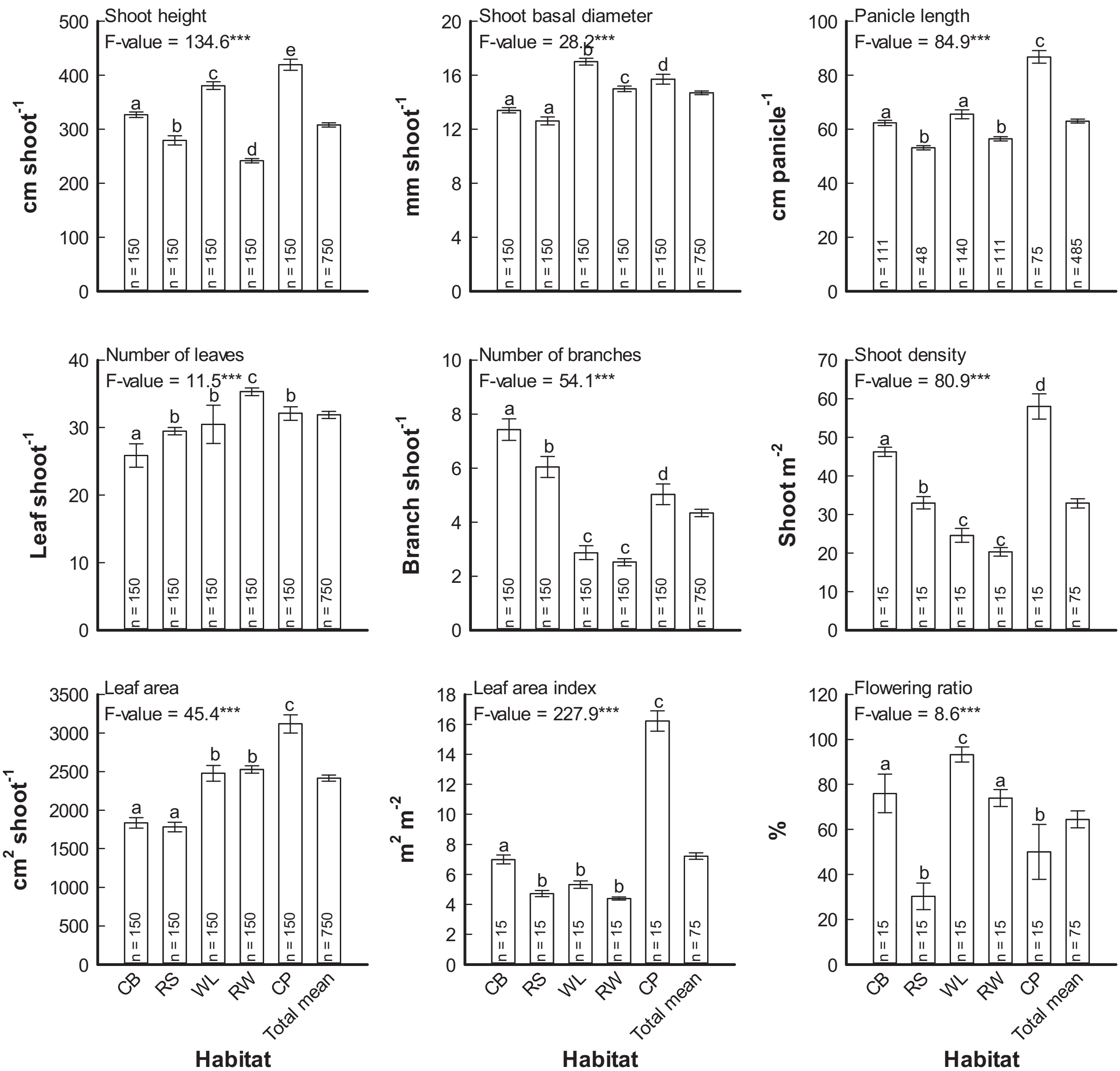

Fig. 2. Variation in density and morphometric parameters of *Arundo donax* in relation to the 5 habitats (CB—canal banks, RS—road sides, WL—waste lands, RW—railway sides and CP—cultivated populations) in Nile Delta, Egypt. Mean and standard error are displayed. *F*-values represent the one-way ANOVA. ***$P < 0.001$. Means followed by different letters are significantly different at $P < 0.05$ according to LSD test.

from 0.5 to 1 g of soil samples using a mixed-acid digestion method (0.0125 M H_2SO_4 and 0.05 M HCl). Salinity and pH of soil samples were measured while using conductivity and pH-meters (Myron L Model DA-1 and ICM Model 41150, respectively). Organic matter was determined by the loss-on-ignition at 550 °C for two hours. Total N was determined in soil samples using a CHN Elemental Analyzer (Yanako CHN Corder MT-5 and Auto Sampler MTA-3). Ca, Mg, Na, K, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn were determined by atomic absorption (Shimadzu AA-6300), and P by spectrophotometer (CECIL CE 1021) when using the ammonium-molybdate method. All these procedures were outlined in Allen (1989).

2.4. Statistical analysis

Before performing analysis of variance (ANOVA), the data of population parameters were tested for their normality of distribution and homogeneity of variance, and when necessary, data were log-transformed. The significance of variation in the population parameters such as shoot height, shoot basal diameter, panicle length, number of leaves and branches, shoot density, leaf area, leaf area index, flowering ratio and biomass in relation to the habitat types were assessed using one-way analysis of variance (ANOVA-1). Significant differences between population means among the 5 habitats were identified using the least significant difference (LSD) test at $P < 0.05$. The significance of variation in the soil properties in relation to the habitat types was assessed using nonparametric Kruskal–Wallis one-way ANOVA. Significant differences between soil means among the five habitats were identified using the Bonferroni test at $P < 0.05$.

Thirty shoots from the cultivated habitat and 120 shoots from the naturalized habitats from the dataset were selected to use as validation dataset, while 120 shoots from the cultivated habitat and 480 shoots from the naturalized habitats were applied to the regression procedure for evaluating the statistical relationships

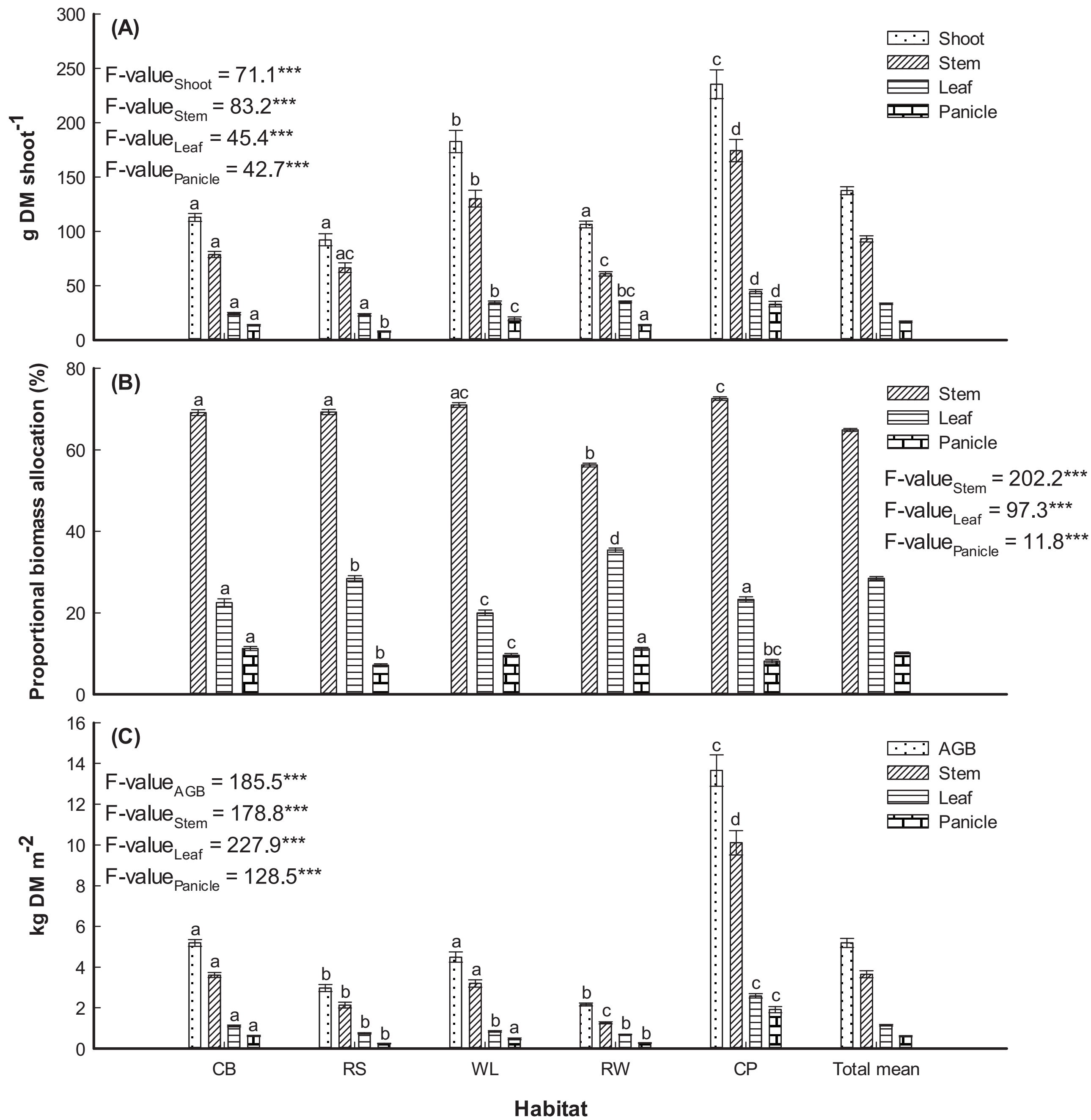

Fig. 3. Variation in individual biomass (A), proportional biomass allocation (B) and total biomass (C) of *Arundo donax* in relation to the 5 habitats (CB—canal banks, RS—road sides, WL—waste lands, RW—railway sides and CP—cultivated populations) in Nile Delta, Egypt. Mean and standard error are displayed. *F*-values represent the one-way ANOVA. ***$P < 0.001$. Means followed by different letters are significantly different at $P < 0.05$ according to LSD test. Lowercase letters pertain to respective organs of *A. donax*.

between shoot height, shoot basal diameter and shoot biomass. Cross validation (Student's *t*-test) was used to evaluate the models based on their predictions using the validation dataset. Because the goal was to develop an accurate equation to estimate shoot biomass, the chosen equation was in the lowest value of *t*-test. Pearson's simple linear correlation (*r*) was calculated to predict the relationship between the population parameters and soil properties. All statistical analyses were performed using SPSS 15.0 software (SPSS, 2006).

In order to detect the ordination of population parameters and habitats along the environmental gradients, Canonical Correspondence Analysis (CCA) was conducted with population parameters, habitat types and soil properties in using CANOCO 4.5 for Windows (Ter Braak and Smilauer, 2002). Before performing CCA, the soil data were transformed by us in taking logarithms. It is due to the fact that they were not normally distributed. Relationships between the ordination axes on one hand, and the soil properties, on the other hand, were tested in using Pearson's simple linear correlation (*r*).

3. Results

Soil of the road sides was richest in organic matter, but lowest in pH; while that of the waste lands had the lowest content of organic matter, nutrients and heavy metals, with the exception of P, Co, Fe, Ni and Pb, which did not differ significantly among studied habitats. Soil of the railway sides had the highest salinity, N, Ca, Na, K, Cd, Cr,

Table 1
Variation in the soil properties (mean ± standard error, $n=3$) of the five habitats (CB—canal banks, RS—road sides, WL—waste lands, RW—railway sides and CP—cultivated populations) supporting *Arundo donax* populations in Nile Delta, Egypt. OM—organic matter. *F*-values represent the nonparametric Kruskal–Wallis one-way ANOVA, degree of freedom (d*f*) = 4. Means in the same rows followed by different letters are significantly different at $P<0.05$ according to Bonferroni test.

Soil property	Habitat					Total mean	*F*-Value
	CB	RS	WL	RW	CP		
Salinity (mS cm^{-1})	2.4 ± 0.1a	2.6 ± 0.2a	0.9 ± 0.1b	4.5 ± 0.3c	1.5 ± 0.1b	2.9 ± 0.3	23.0***
pH	7.43 ± 0.05ab	7.42 ± 0.04a	7.57 ± 0.03bc	7.57 ± 0.04c	7.61 ± 0.03c	7.51 ± 0.02	11.0*
OM (%)	7.2 ± 0.6a	8.4 ± 0.3b	4.1 ± 0.1c	7.7 ± 0.4ab	7.0 ± 0.1ab	7.3 ± 0.3	11.0*
Macro-nutrients							
N (mg g^{-1})	2.3 ± 0.1ac	2.2 ± 0.1ac	0.8 ± 0.1b	3.0 ± 0.5c	1.3 ± 0.1ab	2.3 ± 0.2	14.7**
Ca (mg g^{-1})	27.5 ± 3.2ac	31.4 ± 0.6a	19.6 ± 0.8c	43.9 ± 3.2b	33.4 ± 1.3a	33.6 ± 2.0	19.7**
Mg (mg g^{-1})	7.6 ± 0.3ac	8.9 ± 0.2a	5.7 ± 0.4c	8.2 ± 0.7a	11.1 ± 0.3b	8.3 ± 0.4	13.7**
Na (mg g^{-1})	6.0 ± 0.1a	5.5 ± 0.4a	3.2 ± 0.1b	7.9 ± 0.5c	5.2 ± 0.1a	6.1 ± 0.3	19.7**
K (mg g^{-1})	7.4 ± 0.5a	6.9 ± 0.3a	3.5 ± 0.1b	9.0 ± 0.4c	8.0 ± 0.2ac	7.4 ± 0.4	15.6**
Heavy metals							
Cd (mg kg^{-1})	4.6 ± 0.4ab	3.7 ± 0.1a	3.6 ± 0.1a	5.4 ± 0.3b	4.8 ± 0.1ab	4.6 ± 0.2	15.8**
Cr (mg kg^{-1})	70.9 ± 1.4a	66.7 ± 1.3a	56.8 ± 0.8a	117.1 ± 21.2b	76.9 ± 0.9ab	84.5 ± 8.2	14.1**
Cu (mg kg^{-1})	189.8 ± 9.6a	152.7 ± 2.5a	141.4 ± 2.5a	420.8 ± 89.7b	225.8 ± 4.2ab	257.2 ± 36.9	23.6***
Mn (mg kg^{-1})	1.3 ± 0.1a	1.3 ± 0.1ab	1.0 ± 0.1b	1.3 ± 0.1a	1.5 ± 0.1a	1.3 ± 0.1	11.5*
Zn (mg kg^{-1})	203.4 ± 16.8ab	157.7 ± 7.7a	105.6 ± 3.5a	372.1 ± 86.5b	145.0 ± 7.3a	232.1 ± 34.5	18.8**

* $P<0.05$.
** $P<0.01$.
*** $P<0.001$.

Table 2
Variance analysis for equations used for predicting the shoot biomass of *Arundo donax* in Nile Delta, Egypt. *W*—shoot dry matter (g DM shoot^{-1}), *H*—shoot height (cm shoot^{-1}), *D*—shoot basal diameter (mm shoot^{-1}).

Equation	R^2	Shoot dry matter		*t*-Value	*P*
		Actual	Estimated		
Naturalized populations					
$W=0.65\times H-67.09$	0.648	107.9	113.5	1.03	0.313
$W=15.65\times D-111.70$	0.674	107.9	110.7	0.47	0.639
$W=0.39\times H+10.05\times D-140.99$	0.825	107.9	110.5	0.68	0.500
$W=25.62+11.72\ e^{0.007\times H}$	0.745	107.9	126.2	2.45	0.020
$W=-577.93+500.02\ e^{0.022\times D}$	0.675	107.9	106.9	0.16	0.871
Cultivated populations					
$W=1.27\times H-296.65$	0.913	236.2	235.5	0.04	0.972
$W=35.38\times D-316.68$	0.930	236.2	248.3	0.93	0.382
$W=0.51\times H+21.94\times D-319.66$	0.941	236.2	244.4	0.65	0.535
$W=-170.91+103.21\ e^{0.003\times H}$	0.944	236.2	221.6	1.17	0.279
$W=-345.08+222.75\ e^{0.059\times D}$	0.953	236.2	248.5	1.28	0.243

Cu and Zn; while that of the cultivated populations had the highest pH, Mg and Mn (Table 1).

Significant variations in density, morphological and biomass parameters were depicted between the naturalized and cultivated populations (Figs. 2 and 3). Generally, the naturalized populations along the road sides had the lowest shoot basal diameter, panicle length, leaf area, flowering ratio, biomass of shoot, leaf and panicle and panicle proportional biomass allocation (Figs. 2 and 3). In addition, the naturalized populations along the railway sides had the lowest shoot height, number of branches, shoot density, leaf area index, total above-ground biomass, biomass of stem and leaf, as well as stem proportional biomass allocation (Figs. 2 and 3). In contrast, the cultivated populations had the maximum values for shoot height, panicle length, shoot density, leaf area, leaf area index, total above-ground biomass, and biomass of shoot, stems, leaf and panicle (Figs. 2 and 3).

The shoot height explicated the percentage of 64.8–94.4% while shoot basal diameter explicated the percentage of 67.4–95.3% of the variation of shoot biomass; however, both of them explained the percentage of 82.5–94.1% of the same variation (Table 2). The following regression equations were effective for explaining the variation in shoot biomass in the naturalized and cultivated populations, respectively: $W=-577.93+500.02\ e^{0.022\times D}$; $W=1.27\times H-296.65$; where *W*: shoot dry matter (g DM shoot^{-1}); *H*: shoot height (cm shoot^{-1}); *D*: shoot basal diameter (mm shoot^{-1}). Results of Student's *t*-test indicated that there was no significant difference between the estimated and actual means of the shoot dry weights (naturalized populations: 106.9 versus 107.9 g DM shoot^{-1}, $t=0.16$, $P=0.871$; cultivated populations: 235.5 versus 236.2 g DM shoot^{-1}, $t=0.04$, $P=0.972$).

The dependence of shoot height, number of branches and panicle length on shoot density indicated the density-size effects (Appendix 1). In addition, the increased shoot density was associated with the increased leaf area index and total above-ground biomass. Density, morphology and biomass of *A. donax* were significantly correlated with some soil properties (Appendix 2). Increased soil salinity was associated with decrease in shoot height, panicle length, shoot biomass and total above-ground biomass. A higher pH was combined with the increase in shoot basal diameter, number of leaves, leaf area, panicle length and shoot biomass and the decrease in number of branches. A higher soil organic matter was correlated with taller shoots, increase in shoot basal diameter, flowering ratio and shoot biomass. The increase of soil N was correlated with the decrease in the shoot height, shoot basal diameter, panicle length, shoot biomass, stem biomass, panicle biomass and total above-ground biomass.

The correlation coefficients between the environmental factors and the first two CCA axes (Figs. 4 and 5, Table 3) indicated that

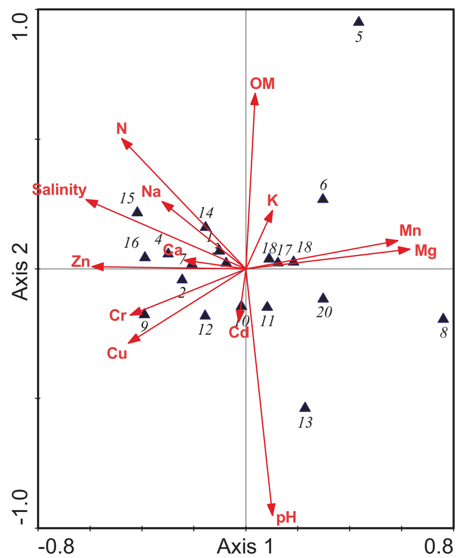

Fig. 4. CCA biplot with soil properties (→) and population parameters (▲). The population parameters are coded as follows: (1) shoot height, (2) shoot basal diameter, (3) panicle length, (4) number of leaves, (5) number of branches, (6) shoot density, (7) leaf area, (8) leaf area index, (9) flowering ratio, (10) shoot weight (g DM shoot^{-1}), (11) stem weight (g DM shoot^{-1}), (12) leaf weight (g DM shoot^{-1}), (13) panicle weight (g DM shoot^{-1}), (14) stem proportion (%), (15) leaf proportion (%), (16) panicle proportion (%), (17) total above-ground biomass (kg DM m^{-2}), (18) stem biomass (kg DM m^{-2}), (19) leaf biomass (kg DM m^{-2}) and (20) panicle biomass (kg DM m^{-2}).

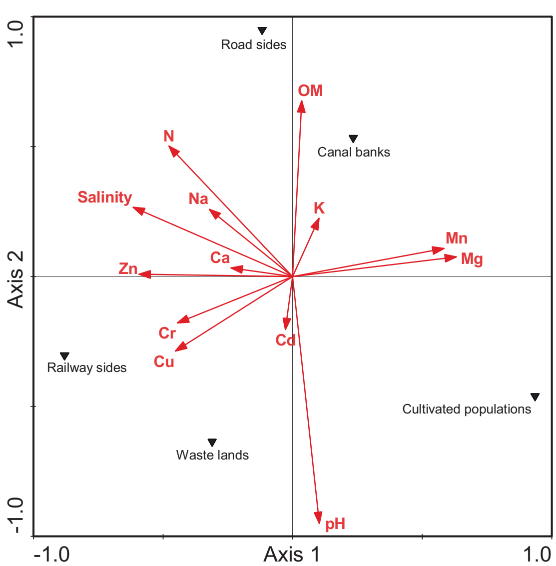

Fig. 5. CCA biplot with the soil properties (→) and the 5 habitats (▼) supporting *Arundo donax* populations in Nile Delta, Egypt.

the separation of the population parameters and the five habitats supporting *A. donax* along the first axis was positively influenced by the gradients of Mg and Mn and negatively influenced by salinity, N, Cr, Cu and Zn. CCA-axis 2 was positively correlated with the gradients of organic matter and N, and negatively influenced with pH.

4. Discussion

Total above-ground biomass of *A. donax* populations in Nile Delta (Egypt) was approximately 2.2–13.7 kg DM m^{-2}. Its previous estimates; on one hand, in the temperate zone were 1.5 kg DM m^{-2} in Germany (Bacher et al., 2001), 0.5–4.7 kg DM m^{-2} in Italy (Angelini et al., 2005; Fagnano et al., 2015), 0.8–7.3 kg DM m^{-2} in Greece (Tzanakakis et al., 2009), and 5.3 kg DM m^{-2} in Turkey (Günes and Saygin, 1996). On the other hand, its estimates in south-eastern and western of USA were 2.3–17.2 kg DM m^{-2} (Spencer et al., 2006; Kering et al., 2012) and in India were 3.6–16.7 kg DM m^{-2} (Sharma et al., 1998). A high solar irradiance, long growing season and favorable growth temperature are probably important factors in determining this high total above-ground biomass (Eid et al., 2010a, 2012, 2013), where temperature and photoperiod most likely play a crucial role in *A. donax* biomass (Mantineo et al., 2009). The observed differences are related to management practices (irrigation, fertilization, harvesting), which seem to affect the biomass of *A. donax* (Nassi o Di Nasso et al., 2010).

A. donax stands are among the most productive plant communities in the world (Angelini et al., 2005). Its cultivated populations in the present study showed exceptionally high biomass (13.7 kg DM m^{-2}), which is higher than that of *Phragmites australis* (5.4 kg DM m^{-2}) in habitats of similar ecological and morphological characteristics (Eid et al., 2010b). Physiological and morphological traits that might support high biomass of *A. donax* including high net photosynthetic CO_2 uptake rates of 37 μmol m^{-2} s^{-1}, lack of light saturation, and little photo-inhibition, had been reported (Rossa et al., 1998).

Environmental factors are of crucial importance to plant establishment and could vary widely even within a specific habitat type (Quinn et al., 2007). Generally, naturalized populations along the railway and road sides has the lowest values for the most measured population parameters, while the cultivated populations has the highest values. This may be related to moisture availability, population management, environmental conditions and/or genetic properties. The railway and road sides were subject to greater stress due to the infertility and shallowness of their soil (Shaltout et al., 1999), as well as to local pollution and drought conditions showed reduction in productivity, CO_2 assimilation and transpiration in *A. donax* (Mann et al., 2013a).

Dimension analysis, as a non-destructive technique, was an alternative to the harvest technique for estimating the phytomass (Whittaker, 1962). The method involved deriving equations that described the growth relationships from intensive measurements of a relatively small number of sample plants. Such equations were then used to estimate biomass from plant characteristics that were more easily measured (such as shoot height and shoot basal diameter) (Spencer et al., 2006). In the present study, we deduced simple equations for predicting shoot biomass of *A. donax* in the cultivated and naturalized habitats while using easy determined shoot height

Table 3
Inter-set correlations of soil properties with CCA axes. Significant values are bolded. OM—organic matter.

N	Soil property	Axis 1	Axis 2
1	Salinity (mS cm^{-1})	**−0.62****	0.27
2	pH	0.10	**−0.95*****
3	OM (%)	0.04	**0.68****
4	N (mg g^{-1})	**−0.48***	**0.50***
5	Ca (mg g^{-1})	−0.24	0.03
6	Mg (mg g^{-1})	**0.63****	0.08
7	Na (mg g^{-1})	−0.32	0.26
8	K (mg g^{-1})	0.10	0.22
9	Cd (mg kg^{-1})	−0.03	−0.20
10	Cr (mg kg^{-1})	**−0.45***	−0.18
11	Cu (mg kg^{-1})	**−0.45***	−0.29
12	Mn (mg kg^{-1})	**0.58***	0.11
13	Zn (mg kg^{-1})	**−0.59***	0.01

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.

and shoot basal diameter. These equations were useful in structural plant modeling (Hanan, 1997). In combination with counts of the number of shoots per m^2 and their height and basal diameter, these equations provided an accurate and time-saving method for estimating above-ground biomass of *A. donax*. Spencer et al. (2006) developed an equation for estimating *A. donax* shoot dry weight from shoot height. Angelini et al. (2009) developed two equations to predict *A. donax* biomass using shoot height and shoot diameter.

Shoot height of *A. donax* ranged between 242 and 419 cm in Nile Delta, Egypt. This range was higher than the previous estimates of 192–339 cm in the temperate zone (Cosentino et al., 2006; Fagnano et al., 2015), but lower than that of 217–550 cm in south-eastern and western of USA (Spencer et al., 2005; Mann et al., 2013b) and of 350–490 cm in India (Sharma et al., 1998). The climatic conditions (Eid et al., 2010a), the location of the population (Bacher et al., 2001) and shoot density (Angelini et al., 2005) were probably important factors in determining this high shoot height.

Leaf area represents a fundamental factor in driving crop growth (Hunt, 1982), as it directly affects light interception and penetration through the canopy and leaf energy balance. Leaves are often smaller in species occupying habitats with low nutrients or low moisture availability (Niinemets and Kalevi, 1994). Leaf area indices are one of the agronomic variables that better summarize the complexity generated by the combination of inner and external factors influencing the structure of plant canopies, being strongly affected by all the interactions between genotype and environmental factors (Soltani and Galeshi, 2002). The present results showed that the cultivated populations and the naturalized populations along the canal banks had the highest leaf area index while the naturalized populations along the railway and road sides had the lowest. These results might be attributed to sufficient moisture in the cultivated populations and the populations along the canal banks compared with the other habitats. Grier and Running (1977) stated that leaf area is a suitable parameter to interpret site water balance relationships of plant communities. Both leaf area and leaf consistency are related to the moisture conditions prevailing in the habitat occupied by the plant. The moisture conditions reflect climatic and soil factors and it may be difficult to distinguish between the effects of either (Werger and Ellenbroek, 1978). Leaf area index of *A. donax* in the present study (4.4–16.2 $m^2\,m^{-2}$) is higher than that reported by Nassi o Di Nasso et al. (2011) for its populations in Italy (5.8 $m^2\,m^{-2}$). Lower leaf area index values in Italy probably resulted from the lower radiation and temperature that characterized their study sites. However, the cultivated populations of *A. donax* in the present study had leaf area index of 16.2 $m^2\,m^{-2}$ which was lower than that of 22 $m^2\,m^{-2}$ for *P. australis* during the peak of the growing season in Lake Burullus (Eid et al., 2010b). This difference was related to the high shoot density of *P. australis* in Lake Burullus (128 shoot m^{-2}). In the present study, the increase in shoot density was associated with the increase in total above-ground biomass and that was comparable to the results of Cosentino et al. (2006), who reported that shoot density of *A. donax* had the most important influence on its total above-ground biomass. Morphology and biomass of *A. donax* were significantly correlated with some soil characters. The present results indicated that shoot height, panicle length, shoot biomass and total above-ground biomass of *A. donax* were adversely affected with the increase of salinity. A similar result was found for *P. australis* in the Danube Delta (Hanganu et al., 1999) and in Lake Burullus (Eid et al., 2010a), where salinity was found to have a pronounced negative correlation with the morphology and population structure of *P. australis*.

The increase of soil N was associated with the decrease in shoot height, shoot basal diameter, panicle length, shoot biomass, stem biomass, panicle biomass and total above-ground biomass. The finding was comparable to the results of Palmer et al. (2014), who reported a negative correlation between N application and biomass yield of *A. donax*. However, some other studies reported a positive correlation (Angelini et al., 2005; Kering et al., 2012), which could be related to characteristic nutrient cycling associated with the rhizome structure of this species (Palmer et al., 2014), and potential association with N-fixing bacteria (Davis et al., 2010). Organic matter was expected to enhance the growth of *A. donax* (Varanini and Pinton, 2001), where a higher soil organic matter was associated with taller shoots, increase in shoot basal diameter, flowering ratio and shoot biomass. Although the soil Cu and Mg varied significantly in relation to habitat types, Mg seemed to be the most influential on many population parameters of *A. donax*. This finding could be related to distinctive functions of Mg, which positively affected the biomass of *A. donax*, as a constituent of chlorophyll and therefore had a major role in photosynthesis (Allen, 1989).

5. Recommendations

Because *A. donax* is tolerant to a wide range of environmental stresses, we recommend its cultivation in the marginal lands (subjected to accelerate erosion) which cannot be used for food crops to reduce its competition with food and fiber crops that require better quality arable land. Its cultivation will have positive effects on environmental quality, such as improvement of soil fertility and reduction in soil loss by erosion due to reducing soil erodibility and increasing vegetation cover.

We developed, for the cultivated and naturalized populations of *A. donax*, simple equations for predicting its shoot biomass from more easily determined shoot height and shoot basal diameter. Because these methods are non-destructive and time-saving, these equations are useful for monitoring the primary production of this plant that should be needed for any management plan.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aquabot.2015.11.001.

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